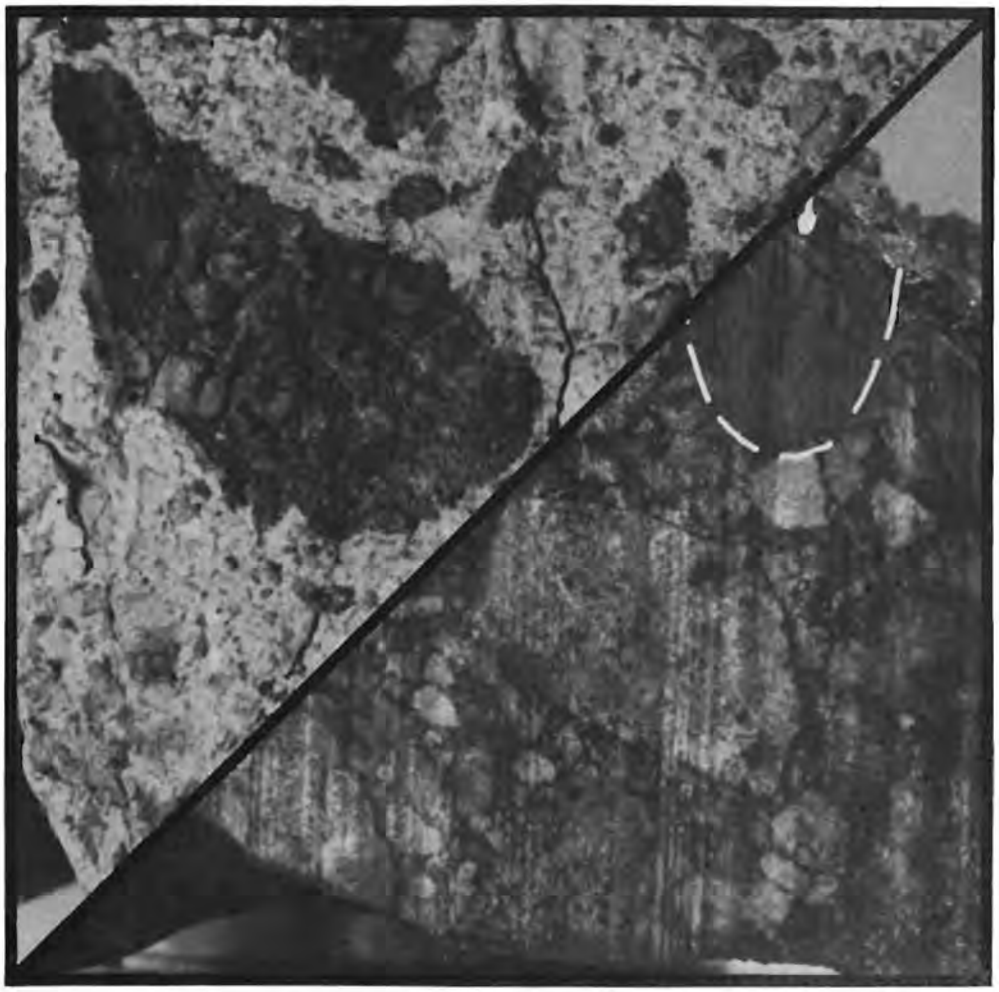
WORKSHOP ON

LUNAR BRECCIAS AND SOILS AND THEIR METEORITIC ANALOGS



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WORKSHOP ON

LUNAR BRECCIAS AND SOILS AND THEIR METEORITIC ANALOGS

Edited by:
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Laurel L. Wilkening

A Lunar and Planetary Institute Workshop
November 9—11, 1981

Lunar and Planetary Institute 3303 NASA Road 1 Houston, Texas 77058

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MEMORANDUM

To: Participants, *Workshop on Lunar Breccias and Soils and Their Meteoritic Analogs* **Date:** May, 1982

From: Renee Edwards, Publications Office

Subject: Errata

Information on how to reference the Workshop on Lunar Breccias is given on the second page of the workshop volume, which we just mailed to you. Unfortunately, this information is incorrect due to the fact that one of the editors' names was left off. The correct way to reference this volume is as follows:

Taylor G. J. and Wilkening L. L. (1982) *Workshop on Lunar Breccias and Soils and Their Meteoritic Analogs*. LPI Tech. Rpt. 82-02. Lunar and Planetary Institute, Houston. 172 pp.

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Cover: Lunar (67015, left) and meteoritic (BTNA78004, right) breccias. Both rocks are fragmental breccias consisting of mechanically-interlocked rock and mineral clasts. The largest clast in the photograph of BTNA78004 is 2 cm long; the largest one in 67015 is 1 cm long.

Contents

Preface

This report documents the results of a workshop on "Comparisons between Lunar Breccias and Soils and Their Meteoritic Analogs," which was held at the Lunar and Planetary Institute November 9–11, 1981. This workshop was the third in a series organized by the Lunar and Planetary Sample Team as part of the Highlands Initiative, an effort organized to help focus research aimed at understanding the early evolution of the moon's crust. However, in contrast to two previous workshops, *Workshop on Apollo 16* (LPI Technical Report Number 81-01) and *Workshop on Magmatic Processes in Early Planetary Crusts* (LPI Technical Report Number 82-01), this workshop was designed to use our knowledge about lunar breccias to help sharpen our understanding of meteoritic breccias and, therefore, of meteorite parent bodies.

I. Workshop Rationale and Format

G. J. Taylor and L. L. Wilkening

Lunar soils and breccias have been studied in detail since the first samples were returned from the Apollo 11 mission. They have been analyzed for their chemical compositions, mineralogy, petrology, physical characteristics, and cosmic-ray, solar-flare and solar-wind exposure histories. Models describing the evolution and dynamics of the present regolith and the ancient megaregolith have been developed. Based on comparisons with terrestrial impact craters, lunar breccias have been classified by their probable locations within or outside craters. The aim of the workshop was to use this extensive body of data and theory to help us understand the evolution of meteorite parent bodies. Although meteoritic breccias have also been studied in considerable detail, there never has been a concerted effort to compare them to lunar soils and breccias. Such comparisons can lead to a better understanding of a number of problems in planetary science:

1) The accretion of the planets and meteorite parent bodies must have involved impacts. Can we see evidence for these accretionary impacts? How would the breccias produced differ from those formed at the present surfaces (the regolith; i.e. "gas-rich" breccias)? Can we distinguish the effects of processes operating during accretion from those that operated before and after accretion?

2) How comparable are the properties of lunar and meteoritic regolith breccias? What do differences in their respective solar-wind inventories tell us about the formation of lunar and meteoritic breccias? Do lunar and meteoritic breccias record different eras of solar activity? What are the significant differences in their exposure histories? How different are meteorite and lunar regoliths in their physical properties (e.g., grain size)?

3) What can we learn about cratering processes on asteroids from studies of lunar and meteoritic breccias? Are differences between lunar and meteoritic breccias due to differences in impact velocities, the population of projectiles (fluxes, size distributions), or properties of the target materials? What effect does chemical composition have on regolith development?

4) How can we date the assembly of regolith (and other fragmental) breccias? What do breccia ages mean? Can we use them to learn about meteorite fluxes or the frequency of impacts in the asteroid belt?

5) What can volatiles tell us about processes on and in meteorite parent bodies? Many gas-rich lunar breccias have large concentrations of volatiles on grain surfaces. Do these reflect a redistribution driven by outgassing of the early lunar crust, as suggested by the presence of ^{129}I and ^{244}Pu decay products? If so, do gas-rich meteorites contain similar surface-correlated volatiles?

6) Remote sensing of planetary regoliths yields information about the uppermost regolith. How do the physical properties of the regolith affect the spectra? Can we use meteoritic breccias as ground truth? How do meteoritic breccias differ from the soils from which they formed?

The workshop was held at the Lunar and Planetary Institute on November 9–11, 1981. Conveners were G. Jeffrey Taylor and Laurel L. Wilkening. Other members of the steering committee were C. R. Chapman, R. N. Clayton, C. M. Hohenberg, F. Hörz, K. Keil, J. D. Macdougall, and G. W. Wetherill. Sixty-six registrants participated in the workshop (see Section VI for a list of attendees) and included experts on terrestrial, lunar and meteoritic breccias, geochronology, remote sensing, cratering phenomena, asteroid dynamics, and regolith modeling.

General topics were introduced by keynote speakers. Each keynote talk was followed by a discussion period. The first day of the workshop was devoted to analytical data on lunar and meteorite samples (petrology, chemistry and chronology) and to a discussion of data obtained for asteroids by a variety of remote-sensing techniques. Discussions during the second day focused on cratering dynamics and regolith modeling and also included some discussion of whether one can identify in meteorites those features that are due to accretion. The third day was devoted to presentation of summaries of the previous two days' proceedings and to further discussion. Summaries of the discussions are presented in Section III of this report.

II. Program

Monday, November 9

Introduction to Workshop
G. J. Taylor and L. Wilkening

Petrology and Chemistry

Discussion leaders and summarizers: E. Scott, A. Basu

Terrestrial Impact Breccias
D. Stöffler

Lunar Breccias
G. Ryder

Lunar Soils and Soil Breccias
D. McKay

Meteorite Breccias
K. Keil

Petrologic Comparison of Lunar and Meteoritic Breccias
G. J. Taylor

Remote Sensing and Chronology

Discussion leaders and summarizers: C. Chapman, C. Hohenberg

Remote Sensing of Asteroids
B. Zellner

Exposure Histories of Lunar and Meteoritic Breccias
D. Macdougall

Chronology of Lunar and Meteoritic Breccias
D. Bogard

Tuesday, November 10

Impact Processes

Discussion leaders and summarizers: F. Hörz, S. Croft

Fluxes and Velocities
E. M. Shoemaker

Cratering Processes
T. Ahrens

Regolith Dynamics and Accretionary Processes

Discussion leaders and summarizers: L. Wilkening, C. Chapman

Modeling the Evolution of Asteroidal Regoliths
K. Housen

Evolution of an Asteroidal Regolith: Granulometry, Mixing, and Maturity
Y. Langevin

Accretionary Processes
S. Rajan

Wednesday, November 11

Summaries of Discussions

Chairman: G. J. Taylor

Summary of Breccia Petrology
E. Scott, A. Basu

Summary of Breccia Chronology
C. Hohenberg, C. Chapman

Summary of Impact Processes
F. Hörz, S. Croft

Summary of Regolith Dynamics and Accretionary Processes
L. Wilkening, C. Chapman

Future Research Directions
G. Wetherill

Discussion of Potential Collaborative Research

Acknowledgements

The conveners thank the Lunar and Planetary Institute for its support, both in running the workshop and in producing this document. We are also grateful to discussion leaders and summarizers for their efforts and to all participants for taking part in lively discussions. Finally, although not an official convener, C. M. Hohenberg conceived the idea for the workshop and was instrumental in the organization; the conveners thank him for his efforts.

III. Discussion Summaries

Petrology of Breccias

E. R. D. Scott and A. Basu

Introduction

Petrological studies of planetary breccias are aimed at elucidating the following: 1) where the breccias formed on planetary surfaces, 2) the provenance of their ingredients, 3) how and when the ingredients were assembled and lithified, 4) the nature and velocity of the projectile(s) involved, and 5) the structure of the planet itself. Achieving these aims requires much more input from theoretical and experimental disciplines. Some areas of agreement and disagreement in the pursuit of these goals are outlined below. In general, disagreements at the workshop concerned details, but for many breccias, especially some types of meteoritic breccias, our ignorance of their origins is immense.

Terminology

An essential requirement for understanding the origins of breccias is a common vocabulary for all breccia petrologists, irrespective of the planet they are studying. Communications in the past have been impeded by disagreements on terms. For example, rock fragments in meteoritic breccias have been called lithic fragements, lithic clasts, exotic inclusions, xenoliths and lithic inclusions (see abstract by K. Keil). Fortunately, Stöffler *et al.* have established a classification scheme for lunar breccias (see abstracts by D. Stöffler and G. Ryder) which is accepted by all breccia petrologists.

Lunar breccias

G. Ryder showed that, in general, there was little ambiguity in classifying lunar breccias. Textures in the various kinds of breccias are well understood. For example, textures of melt breccias are dependent on the proportions of clasts and melt. However, relating texture to a genetic process is not always easy; for example, suevitic breccias (those with cogenetic clasts and melt) are difficult to identify. The chemical composition of breccias can generally be accounted for by mixtures of known rock types. However, KREEP components are poorly defined, volatiles (as in some meteoritic breccias) do not obey simple mixing rules, and impact melt compositions (unlike terrestrial examples) frequently cannot be accounted for by their inventories of clasts.

Regolith breccias from the moon appear to be reasonably representative samples of the regolith (D. McKay). Modal abundances of constituents in the only regolith breccia that has been analyzed match those of soils reasonably well. Clearly, more data comparing lunar soils and regolith breccias are needed before it could be concluded, for example, that meteoritic regolith breccias are good samples of asteroidal regoliths. Lunar soils are very heterogeneous, but no regolith breccias have been studied to see if they show the same heterogeneity. Comparisons of weakly consolidated and tough regolith breccias were also suggested.

Meteorite breccias

K. Keil and G. J. Taylor demonstrated that the classification scheme of Stöffler *et al.* for lunar breccias provides an excellent basis for understanding a wide variety of meteoritic breccias which formed on at least six or eight different bodies. They described examples of all kinds of breccias (e.g., fragmental, granulitic and melt breccias) among various types of meteorites. One type of breccia not found elsewhere is the "primitive chondrite breccia." It consists of rock fragments in a matrix of primitive components (chondrules, opaque matrix, etc.), which were not previously consolidated into rocks (E. R. D. Scott and G. J. Taylor). D. W.

Sears argued that there was a continuum between these breccias and fragmental breccias, which are entirely composed of chondrite clasts.

Clasts in chondrite breccias are generally fragments of well-characterized rock types. Exceptions include K-rich melt clasts in LL chondrites and the unequilibrated material in some regolith breccias (Keil). Differences between regolith breccias are not well documented, but suggest, for example, that the amount of unequilibrated material in the regolith of the parent body varied with time. Chondrules did not form in asteroidal regoliths nor in large impacts between asteroids (Taylor).

Among differentiated meteorites, there are more unknown rock types represented in the clasts of achondrite and mesosiderite breccias than there are in ordinary chondrite breccias (R. H. Hewins and H. Takeda). Some breccias in both these meteorite groups may have formed during accretion of planetesimals. More oxygen isotopic data on clasts are needed to test this idea. Hewins emphasized the diversity of breccia types among howardites: some are regolith breccias, others may have formed in ejecta blankets.

Differences and similarities between lunar and meteoritic breccias are, in general, ill-defined and not well understood. Apart from direct effects of planetary size on breccia formation, some differences in lunar and meteoritic breccias may result from processes which are unique to meteorites. Three such processes of breccia formation were discussed: 1) accretion of planetesimals when impact velocities were probably lower, 2) fragmentation and reassembly of asteroids (see A. E. Rubin *et al.*), and 3) spallation (see T. J. Ahrens and J. D. O'Keefe). The petrological characteristics of breccias formed by these processes are not well established.

Future work

Some other areas where more petrological studies were proposed are listed below.

1) More studies of lunar regolith breccias using the techniques developed for lunar soils, and of lunar granulitic breccias to identify the source of heat responsible for their metamorphism.
2) Collaborative studies of large meteorite regolith breccias using the wide range of techniques available. Search for variations in the concentrations of solar-wind gases, proportions of various clasts and other parameters.
3) Studies of carbonaceous chondrite breccias. Are some carbonaceous chondrite breccias similar to ordinary chondrite breccias? S. Rajan suggested that Mokoia might be one such example.
4) Detailed studies of breccias from Antarctica; e.g., the regolith breccias, Yamato 75028 (T. Ohta and H. Takeda) and Allan Hills A77215.
5) Incorporation of breccia classifications into catalogs of meteorites and lunar rocks. This fundamental information is presently omitted.
6) Further studies of impact processes in non-cohesive targets. There are no terrestrial examples and little experimental data. The process of shock lithification is poorly understood.

Properties and Dynamics of Asteroidal Regoliths and the Relation to Accretionary Processes

L. L. Wilkening

Observed Properties of Asteroids

B. Zellner summarized for the workshop the available evidence about the physical nature of asteroids. The remote-sensing techniques measure only the surfaces or uppermost surface layers of asteroids, so that information about interiors is only inferential. Polarimetry demonstrates that asteroids have dusty surfaces, similar to dust-covered rocks. Infrared measurements indicate that asteroids, including bodies as small as 433 Eros, have a thermally insulating layer at least a centimeter thick. Radar measurements are capable of probing still more deeply into asteroids, but the implications of the recently obtained data are still not fully understood. Asteroids appear "rough" to radar, but it cannot be easily determined whether the scale of roughness is on the meter scale or on the scale of the body itself (kilometers). The data have been interpreted as being compatible with regoliths.

Observations of asteroids as they rotate indicate that individual bodies have a high degree of compositional homogeneity. Any changes in color, albedo, spectrum, etc. observed as different hemispheres rotate into view are small or absent. Whether this means that an asteroid is compositionally homogeneous, or simply that ejecta from the last large crater has blanketed the body with material from a single location, cannot be determined. Hirayama families are groups of asteroids believed to be fragments from precursor bodies involved in a supercatastrophic collision. Impact probabilities would imply that most fragments are due to the largest body. Most of the large fragments have similar spectra, consistent with the idea that the precursor body was of homogeneous composition throughout its bulk. Some smaller families, however, show great compositional diversity implying that the precursor body was geochemically differentiated. (Perhaps the smaller families are somehow "unreal" despite the formal statistical estimates that they cannot be due to chance.)

Various observations indicate that asteroid surfaces do not undergo the same kind of optical maturation as is observed for the moon. Whether this is due to differences in the impacting environment (e.g., lower impact velocities in the belt), or reflects different compositions that respond differently to the processes of maturation, is not known.

Recent work reported by Zellner *et al.* (1981) has identified a striking pattern of compositions of main belt asteroids as a function of distance from the sun. It had been known before that the so-called S-types, which may be ordinary chondrites (although stony-irons and disrupted/reassembled achondrites cannot be ruled out), predominate in the inner asteroid belt while the black C-types thought to be of carbonaceous composition dominate in the outer half of the belt. In addition to these trends, Zellner reports that the rare E-types occur at the inner edge of the main belt and that the M-types predominate in between the maxima in the distributions for S and C. Furthermore, a new type designated "P" is populated only near the outer edge of the main belt and beyond, while the D-types are most common among the Trojans, far beyond the main belt. Thus there is a systematic ordering of asteroidal materials with distance from the sun. Whether this reflects primordial compositions or subsequent processes of implantation or evolution of asteroids is not yet known.

Dynamics of Regoliths and Megaregoliths

The development of regoliths on asteroids (i.e., meteorite parent bodies) is different from the well-studied case of the lunar maria for several reasons. The impacting flux of projectiles is greater within the asteroid belt than on the moon. But, most importantly, the lower gravity on asteroids results in much more widespread distribution of ejecta. Lower gravity also results in appreciable loss of ejecta from smaller asteroids. Asteroidal surface material is either buried or ejected resulting in less reworking than on the lunar surface. Furthermore, asteroids may be entirely broken up by large catastrophic collisions; the pieces may reassemble to form a new body that is composed of megaregolith throughout, or the pieces may fly apart permanently.

Several features of the impact environment in the asteroid belt serve to modify the importance of processes associated with regolith evolution on the lunar surface. For instance, there is a smaller percentage of micrometeoroids (e.g., of cometary origin) relative to big projectiles in the asteroid belt compared with the lunar environment. Combined with the overall lower average impact velocities in the belt, one expects formation of fewer agglutinates, microcraters, and less comminution of small particles relative to effects due to large events.

At present there is relatively poor understanding of the physical effects of large impacts on the character of regoliths. Among the poorly understood effects and parameters are crater-size scaling, the impact energy necessary to fracture an asteroid, the importance of spallation of surface layers as a response to a large impact, the degree of shock comminution of the interior of an asteroid, and processes of lithification.

One major area of uncertainty relates to the impact flux in the asteroid belt. The number of asteroids smaller than 10 km in diameter is not well known, and there is essentially no information about the population smaller than 1 km in diameter down to centimeter-scale meteoroids. Comparisons of the impacting fluxes on the moon and asteroids, reported by E. M. Shoemaker, suggest that there has been only about a 6-fold higher cumulative cratering rate on the larger asteroids compared with the moon (not considering possible higher fluxes in one or both locations in the past). This estimate is lower by one-half to one order of magnitude than the fluxes used by earlier workers. The problem was not resolved at the workshop, although it was agreed that there is a paucity of data available to answer the question definitively.

Models developed by Y. Langevin and his co-workers and by K. Housen and his colleagues are in fairly good agreement about the nature of regolith development on asteroids. Disagreements are never more than a factor of a few (in total regolith depth, for instance) and relate primarily to differences in modeling ejecta velocity distributions. Both groups agree that episodic blanketing of asteroid surfaces by widespread ejecta results in less reworking than occurs on the moon. Thus asteroidal regoliths are deeper and coarser, and individual grains are only rarely exposed at the surface. These model predictions are in good agreement with the qualitative differences between meteoritic and lunar regolith breccias (lower track densities, lower gas contents, larger particle sizes, etc.). Quantitative comparisons of meteorites with the models are limited by uncertainties in the input parameters. In addition, as Housen emphasized, the inherently stochastic nature of the regolith development process results in uncertainties of a factor of a few just due to random chance.

Neither Housen's nor Langevin's models treat the complicated question of megaregolith development. There is good reason to believe that asteroids are fragmented (and reaccumulate) on timescales shorter than the age of the solar system. This idea, which has been advocated by D. R. Davis, C. R. Chapman, and others, is now gaining some support from meteoritic studies. For example, Rubin *et al.* (see abstract this volume) presented evidence concerning the cooling histories of ordinary chondrites that point in the direction of disrupted and reassembled chondrite parent bodies. The different cooling rates found in single meteorite samples seem to require that materials that evidently cooled slowly at depth have subsequently been rearranged and located in a near-surface environment to become converted into a regolith breccia.

One important area of study that has been largely neglected so far concerns the early history of regolith development in the asteroid belt, e.g., in the earliest accretionary epochs or during subsequent transitional epochs prior to, and during, the late-heavy bombardment epoch in planetary cratering history. The Langevin and Housen models (see abstract this volume) could be studied with a range of input parameters appropriate for different models of planetesimal populations or earlier asteroidal populations. This has not yet been done. One must be careful, however, in piling too many uncertainties on top of one another. There are already many parameters that are poorly understood in the case of the modern-day solar system.

Related to the regolith evolution models are some recent studies that attempt to link asteroid parent bodies with meteorites. Chapman described recent work by himself and R. Greenberg that considers the collisional evolution of asteroids and resulting body strengths of asteroids as a fundamental input to their meteorite production. They suggest that large cratering events liberate most meteorites from parent-bodies; the highest velocity ejecta most readily escape and reach resonances capable of transferring them into Earth-crossing orbits. In the Greenberg-Chapman model, the smaller asteroids are especially weakened by processes of disruption, reassembly and megaregolith formation; therefore, meteorites are preferentially derived from larger, stronger bodies.

Accretionary Processes

Regolith models have been quite successful in explaining the appearances and radiation histories of most brecciated meteorites. The regolith models are based on collisional processes, and it should be recognized that their predictive and explanatory power is limited solely to the post-accretion era. One of the motivations for devising such models was to be able to disentangle the effects of collisions from those of earlier processes which operated to form meteoritic matter and the parent bodies. In particular one hoped to be able to identify the effects of accretion in primitive meteorites, especially the ordinary and carbonaceous chondrites.

Gas-rich ordinary chondrites are similar to gas-rich achondrites in all the features that lead to the appellation "gas-rich." This includes abundances of noble gases, maximum observed solar-flare track densities, percentage of solar-flare irradiated grains, and occurrence of solar-flare track density gradients. Hence, it seems that a common set of processes, as modeled, can account for both the ordinary chondritic and achondritic gas-rich meteorites.

In the case of carbonaceous chondrites (CI's and CM's) the mineralogy is largely a product of aqueous processes which must have taken place in the parent body and may or may not have been contemporaneous with brecciation processes. Because of this, carbonaceous chondrites cannot be explained solely as products of condensation and accretion modified by brecciation and comminution, as can the ordinary chondrites and achondrites. There are also problems in explaining the radiation history of carbonaceous chondrites. Carbonaceous chondrites have very short ($\leq 10^6$ yr.) cosmic-ray exposure ages. For some meteorites the recent exposure as measured by ^{26}Al is the same integrated exposure as measured by ^{21}Ne. This implies that the exposure the material received in the parent-body regolith must have been less than the marginally measurable difference between the two ages. As the ages are accompanied by rather large uncertainties, in practice this means, in most cases, that the parent-body exposure could really be 10^5–10^6 yr. This fits into regolith models, but just on the ragged edge.

The qualitative differences between the irradiation records of gas-rich carbonaceous chondrites and other gas-rich meteorites are more difficult to account for than the exposure ages. In fact, carbonaceous chondrites were not included among gas-rich meteorites for many years because their relatively lower contents of Helium-4 and ambiguous neon isotope ratios did not make them as easily recognized as gas-rich by these two traditional criteria as other gas-rich meteorites. When the solar-flare particle track records were studied, it was found that they too differed from those of other gas-rich meteorites. The total track densities were lower and fewer grains showed gradients in density on one side or on more than one surface. It appears that on the average the carbonaceous chondrites experienced less exposure at the very surface of the meteorite parent body. Or in other words, the average material we have to study was more shielded in its parent-body environment.

Explanations that have been given for the differences fall into two groups: (1) those calling on the low strength of carbonaceous materials to account for a different response of the weak carbonaceous chondrite parent bodies to the collisional environment of the asteroid belt; and (2) the suggestion that the carbonaceous chondrites were irradiated in the early solar system as decimeter-to-meter size bodies prior to accretion (Goswami and Lal, 1979). The carbonaceous chondrites remained an enigma at the conclusion of the workshop.

On the basis of the understanding of regolithic processes that was achieved, it was agreed at this meeting that we can identify some components in chondrites which are not products of collisional processes on meteorite parent bodies. For the first time, a consensus developed that chondrules predate the collisional processing of asteroidal material. Chondrules then join Ca, Al-rich inclusions (CAI's) as primordial chondritic constituents that accreted to form meteoritic parent planets.

In conclusion, it seems the models of regolith evolution show that collisional processes must have had a significant effect on the surface materials on small bodies. A thorough study of the lunar samples and meteorites has shown that although brecciation and comminution processes operated on meteoritic parent material, the collisional environment in which meteorites formed was milder than the moon's. Most meteorites show lesser effects of collisional melting and comminution than do lunar soils and breccias. The regolith models show, in fact, that blanketing by successive layers of regolith protects newly formed regolith until its ejection. An additional mechanism for protecting brecciated asteroidal material from further processing might be deep burial as a result of catastrophic fragmentation and gravitational reassembly of the parent body.

References

Goswami J. N. and Lal D. (1979) *Icarus* **40**, 510.
Zellner B., Tedesco E. F. and Tholen D. J. (1981) *Bull. Amer. Astron. Soc.* **13**, 717.

Chronometric Constraints

C. M. Hohenberg

Petrographic similarities suggest that lunar and meteoritic breccias formed by similar processes. These processes certainly must involve lithification by impact within the regolith of a parent body. In spite of the obvious parallels, such comparisons must be tempered by known differences in time, place, and scale. Few, if any, meteoritic breccias are likely to have originated on a lunar-sized parent body; surviving lunar breccias formed nearly a billion years after most meteoritic breccias; and meteorite parent bodies were likely to have been several times farther from the sun than is the moon. Nevertheless, the relatively well-understood processes occurring in the lunar regolith can serve as a standard of comparison and establish some important constraints on conditions in the regoliths of meteorite parent bodies.

Lithification in Regoliths

Meteoritic and lunar breccias share many of the same features. They both usually contain large quantities of solar-wind rare gases and solar-flare particle tracks. Gradients in the density of solar-flare tracks are often observed in individual irradiated grains of both. Micrometeorite impact pits are also observed in both, although their abundance is lower among meteoritic breccias. Agglutinates have been observed in at least two gas-rich meteorites (Fayetteville and Bununu). These features are indicative of residence in a planetary regolith prior to lithification. Differences in the effects point out major differences in scale or duration of exposure at the surface, or both. Specific comparisons can be summarized as follows: 1) Solar-wind rare gases are typically two orders of magnitude more abundant in lunar breccias than in meteoritic gas-rich breccias. 2) Solar gases contained in lunar breccias are similar to those in modern lunar soils and are more mass-fractionated than solar gases in meteoritic breccias. 3) Solar-flare particle tracks are less abundant by 1 to 2 orders of magnitude in grains extracted from gas-rich meteorites than those from lunar breccias. Almost all grains in gas-rich lunar breccias appear to have been irradiated, whereas this is not true in general for the gas-rich meteoritic breccias. 4) Both show anisotropic solar-flare track gradients, suggesting irradiation under constrained geometry, such as within a regolith, rather than as unconstrained free grains in space.

While these similarities make a strong case for the lithification of meteoritic breccias within the regolith of their parent bodies, they still leave open the questions of when the final assembly occurred and how long the fragments resided unconsolidated in such a regolith.

Solar and Micrometeorite Effects

Differences in solar-wind noble gases, solar-flare track densities, and microcraters indicate that the near-surface residence times were perhaps 2 orders of magnitude less for meteoritic breccias, assuming similar solar-wind fluxes. This corresponds to solar-wind exposure times of about a year for the individual grain surfaces in meteoritic breccias. Comparisons between average solar-flare track densities suggest that typical irradiated meteoritic grains were likely within a centimeter of the regolith surface for times on the order of 100 years. These order-of-magnitude estimates do not take into consideration the possibility that not all grains are carriers of solar gases nor the observation that not all grains are irradiated. They do serve to set boundary conditions on viable models for parent-body regoliths.

Galactic Cosmic Rays

Further constraints are set by the absence in meteorites of prolonged exposure to galactic cosmic rays during residency in regoliths. The measured accumulation of stable nuclides produced by the interaction of galactic cosmic rays with suitable target nuclei in the meteorite provides a measure of the cumulative time the sample spent within about a meter of the surface. Cosmic-ray exposure ages based upon radionuclides, on the other hand, determine the duration of recent (within several halflives) exposure to cosmic rays. This presumably occurred as the result of recent collisional events producing meter-sized objects. Cosmic-ray exposure ages based on ^{21}Ne and ^{38}Ar (stable nuclides) and ^{26}Al and ^{53}Mn (radionuclides) show no detectable differences, thus allowing only very short pre-compaction exposure times. The presence of large amounts of solar-wind gases limits the precision in some cases, but it can be established with certainty that the duration of pre-compaction exposure was extremely short ($<$ 100,000 years) in the case of CM and CI meteorites and was less than a million years in other gas-rich meteorites (see abstract by J. N. Goswami and K. Nishiizumi).

Compaction Ages

The time of regolith residence can be constrained, in at least some objects, by radionuclear compaction ages. J. D. Macdougall discussed fission track studies of the CI and CM meteorites, which indicate that compaction must have occurred more than 4.2 billion years ago. Tracks originating in Pu-rich matrix material are easily detectable on the edges of Pu-free olivine grains. Assembly must therefore have occurred while ^{244}Pu was still extant and the objects must have remained essentially undisturbed since that time. As discussed by D. Bogard, other classes of brecciated meteorites contain clasts whose internal radiometric clocks have been reset more recently than 4.2×10^9 yr. Other meteoritic breccias show similar effects. One must therefore allow for the possibility that significant regolith activity occurred on other meteorite parent bodies more recently than is indicated for the CI and CM parent bodies. Other explanations have also been suggested. Repeated impacts seem to be able to reset radionuclear clocks more effectively than single events and the apparent radionuclear ages observed for many clasts in highland breccias may reflect such cumulative disturbance. This provides the possibility of post-compaction disturbance of radionuclear clocks in meteoritic breccias as well. C. Hohenberg pointed out that shock can produce nonthermal alteration of isotopic structure. Until more data is obtained the question must remain open, but the present evidence seems to weigh in favor of a rather extended period of regolith activity in the early solar system.

The effect of shock is manifested in other ways in the lunar regolith. It has long been known that solar-rare gases are fractionated with respect to those in gas-rich meteorites. The traditional interpretation attributes the mass fraction to saturation and resulting loss of the lighter species, given the higher rare gas concentrations in lunar soils and breccias. Evidence presented by P. Signer strongly suggests that this effect is not one of saturation but is due to the nonthermal effects of repeated impacts. The distribution of solar-flare track densities and the abundances of all the rare gases seems to be similar and independent of soil maturity (or rare gas content). Such an effect can only occur if the process leading to the preferential loss of the lighter rare gases is independent of its concentration. It is consequently not a process that involves saturation and probably not even thermal diffusion, but likely involves mobilization caused by multiple shock events.

Impact Processes

S. K. Croft

Impact processes are fundamental to the mechanical formation of breccias and regoliths on the moon and the meteorite parent bodies. The formal contributions to this session of the workshop were broad in scope and addressed very different aspects of breccia formation. To focus the broad range of details mentioned in the contributions and discussions, the major points raised have been organized into four sections.

Flux Histories

Estimation of the integrated absolute flux, or "total dose," of objects colliding with a given planetary surface constitutes the first step in estimating the depth and maturity of the regolith on that surface. The size distribution and spectrum of velocities characterizing populations of impactors vary both from planet to planet in the solar system and in time on a particular planet. A given impactor flux can be "translated" into a crater production rate—which is directly related to regolith formation—by using a crater scaling relation. Such scaling relations are based partly on theory and partly on observation, and become increasingly uncertain with increasing crater size. Crater scaling relations in common use generally relate an observed crater diameter to the total energy of the impactor with some provision for the planetary surface gravity. However, other possibly important factors that enter directly into crater formation include the impactor's density and velocity (momentum), the "strength" (measured in many different ways), the porosity and density of the planetary crustal materials, and possibly even the absolute size of the event, since processes like dynamic fracture are dependent on strain rate and the duration of high shock pressures. Consequently, the translation of flux to cratering rate is subject to considerable uncertainty.

E. M. Shoemaker estimated the current cratering rate on the moon and three asteroids—Ceres, Vesta and Pallas—for comparison. The flux was estimated from the observed sizes, numbers and orbits of asteroids and long and short period comets. He used an energy-diameter scaling law with corrections for gravity. For the asteroids, the contribution of the comets to the total cratering rate was small compared to the contributions from other objects in the asteroid belt. In the lunar case, about half of the cratering rate was due to long-period comets and half to earth-crossing asteroids. The cratering *rates* on Ceres and Vesta were calculated to be about three times that of the moon, a low ratio that was surprising to both the speaker and the audience as it implied a significantly smaller cratering rate among the asteroids than had previously been assumed. The cratering *flux* at Ceres and Vesta, however, was estimated by Shoemaker to be ~10 times lunar. This flux, however, is still lower than previous estimates; it is particularly in conflict with all fluxes employed in recent regolith modeling attempts that require successive blanketing events on very rapid time scales to obtain the observed (short) exposure ages of meteoritic components.

Melt Production and Dilution

One problem in the meteoritic breccia formation is the paucity of regolith melt compared to the lunar regolith. Several contributing factors were considered. T. Ahrens reviewed calculations that showed that the ratio of melt volume to projectile volume increases as the square of the impact velocity above a threshold velocity. Below the threshold velocity (~7 km/sec for rock-on-rock impacts), the pressures generated in the impact are insufficient to produce melt, and the volume of melt drops rapidly to zero. Consequently, the absolute melt productivity is strongly affected by the lower average impact velocity for the meteorite parent bodies compared to the moon. This is consistent with the flux calculations made by Shoemaker who found mean impact velocities of ~5 km/sec on Ceres and Vesta and ~15 km/sec on the moon. The estimated mean impact velocity for Pallas is ~11 km/sec, however, which implies that velocity differences may not be the whole answer.

Another possible factor is surface gravity. The crater produced by a given impact increases in diameter with decreasing gravity ($D \propto g^{-1/6}$); craters on Ceres have diameters about twice those on the moon (assuming similar impact conditions). Consequently, the relatively small volume of melt produced by the 5 to 7 km/sec impacts is mixed with roughly an order of magnitude more ejecta on the asteroids than on the moon, leading to a dilution of the melt component by the same factor. In addition, the melt produced in an impact has the highest ejecta velocities, and, as discussed by Ahrens, is the material most likely to be lost by ejection at velocities greater than the escape velocity. On asteroids, where the surface gravity is small, much of the melt will be directly ejected at velocities exceeding the escape velocity, and thus be completely lost to the zone of regolith formation on the asteroid's surface. Calculations also show that the volume of material subjected to pressures sufficient for brecciation greatly exceeds the volume of material subjected to sufficient pressures to cause melting during *any* impact. The volume of brecciated material also greatly exceeds the volume of the colliding object. Even in erosional regimes, where a larger mass of material is gravitationally lost than is gained from the colliding object, a substantial volume of breccia will be retained, allowing substantial regoliths to be built up.

Porosity Effects

Computer calculations of impacts, such as those reviewed by Ahrens, are usually performed assuming a continuous target medium with zero porosity. This is due both to the incomplete understanding of the physical behavior of fractured and porous material under impact conditions and to the difficulty of representing such behavior in a computer program. For impacts in real regoliths, however, porosity is an important factor in several processes:

a) Melt production: Shock pressures generated in impacts in porous media at a given impact velocity are generally lower than the pressures obtained in zero-porosity targets. However, the extra compression gained by closing the voids in a porous target enhances shock heating and allows melt production to occur at lower velocities than the threshold velocity calculated for non-porous media. In shock compaction experiments by F. Hörz and R. Schaal on particulate basalt, melt was found to occur at impact velocities near 5 km/sec.

b) Ejection velocities: The lower pressures and greater percentage loss of impact energy to heat in porous targets leads to lower ejection velocities for the bulk of the ejected material. This effect lowers the cumulative ejected mass versus escape velocity curves calculated by Ahrens and implies that asteroids with rubbly surfaces accrete more efficiently than asteroids with surfaces of bare, consolidated rock. An important aspect of shock effects in porous versus non-porous targets is the fact that shock attenuation rates are dramatically different; i.e., very fast in porous materials compared to non-porous materials. This may be important for "rubbly" old asteroids.

Finite Targets

Ahrens discussed both old and new computer calculations of pressure decay along the axis of symmetry in vertical impacts into competent rock (gabbroic anorthosite) and the results of spallation studies in finite basalt spheres by A. Fujiwara. The rate of pressure decay—and consequent changes in modes of brecciation—falls into three regimes: the near field where the rate of decay is small, the far field where the rate of decay is large (though constant), and a "late spall regime" where antipodal spalling in finite targets is governed by the dynamic tensile strength of the target. Agreement between experiment and calculation in the far-field regime is good. The rate of pressure decay in the far field increases slowly with increasing impact velocity, but is nearly independent of projectile density. However, these idealized results, both experimental and theoretical, must be modified somewhat upon application to real asteroids where porosity and internal fractures are probably present. Porosity in the target greatly increases the rate of pressure decay, reducing the volume of brecciation and diminishing, if not eliminating, spalling near the antipode, even for comparatively large impacts. This effect is tangibly illustrated by the impact experiments of Hörz, who used spheres composed of porous mortar as targets, in which no antipode spalling was produced, even for craters ejecting practically half of the entire target sphere. Hörz also showed spallation of a granite sphere characterized by removal of the surface of the entire forward hemisphere, leaving a central core attached to the nearly unfractured rear hemisphere. Hörz thought that the lack of rear spallation in this case was due to the low velocity of the projectile. While it is apparent that both the calculations and experiments that have been performed are useful guides to possible effects of impacts on asteroid-sized objects, the as yet unevaluated dependence on velocity and size in spallation and brecciation need further elucidation.

In brief, our knowledge regarding the cratering history of asteroidal objects as well as those of returned lunar materials is still fragmentary. Significant advances may only come about if we better understand the complex physics of impact events and ultimately of events of dramatically different sizes. It is clear, however, that the manifestations of the cratering process may differ from planet to planet in response to variable target properties as well as total target mass. Considerable progress has been made in understanding impact cratering in infinite targets, but we know little about the impact physics leading to partial, if not complete, destruction of asteroid-sized objects.

IV. Future Research Directions

George W. Wetherill

It has always seemed to me somewhat presumptuous for a committee of experts to write reports in which they tell other people what work they should do in the future. It would certainly be worse for an individual who isn't really an expert on breccias to do this. Therefore, I will simply share some thoughts that have been running through my mind as I listened to the results of those who are actually doing the arduous laboratory and field work that has brought us to the present quite advanced state of knowledge on this subject.

When we tell government officials and the general public why it is necessary to study asteroids and meteorites, it is customary to explain that these primitive objects are samples of the formative solar system. We emphasize their unique property of having to a large degree escaped the geological processing that has all but erased the record of this early history on larger planetary bodies. I believe that the greatest future progress will come as a result of a growing recognition that this is literally true, not merely words put into a committee report to inspire funding.

A strong link has now been established between meteorites and asteroids. Studies of meteoritic breccias and the physical properties of asteroids have played a major role in forging this link. However, the establishment of this relationship should not be regarded simply as an end in itself, but as a first step in the opening of a new field of planetary science, one that will utilize the potential contribution of combined meteoritic and asteroidal studies to learn about events and conditions during the veiled period of history between ~ 4.0 and 4.5 b.y. ago. If this point of view is accepted, rather than decried as a hopeless quest for some "holy grail," this will determine the direction of future work in this area of science, without the need of a committee of experts to tell us what to do.

For example, despite recent major progress in spectrophotometric studies of asteroids (Feierberg *et al.*, 1982) a unique correspondence between asteroidal and meteoritic classes has not yet been achieved. Furthermore, there are many serious gaps in the quantitative dynamic theory of the mechanisms by which asteroidal fragments are perturbed into earth-crossing orbits. From the point of view supported here, really understanding the asteroid-meteorite connection is a prerequisite for progress toward the goal of understanding early solar system history.

The reason is that the present structure of the asteroid belt was established during the time period under consideration, 4.0 to 4.5 b.y. ago. The present-day asteroids are likely to be the residue of a much larger and heterogeneous generation of planetesimals (Chapman and Davis, 1975), some indigenous to the asteroid belt, and others of external origin (Wasson and Wetherill, 1979). Meteorites are samples of these ancient bodies, provided to us by an inexpensive but not well-planned sampling process that has caused the rock samples to lose their labels. The labels need to be put back on, not just plausibly enough to define a consensus that will discourage further inquiry, but in a way that is really correct. This represents a continuing challenge that is difficult but of extreme importance. A premature consensus on this matter could lead an entire generation of workers down the wrong path.

Another example stems from the fact that the last few years have seen the development of the first quantitative models for the development of regoliths in the present-day asteroid belt (Housen *et al.* 1979a, b; Langevin and Maurette, 1980, 1981). These models provide an important starting point for relating the detailed laboratory data obtained from meteorites to processes on asteroidal surfaces. But again, fullest utilization of this meteoritic record will require distinction between the effects of the relatively mundane present asteroid belt, and those that are clues to the profound questions of solar system origin.

It seems to me that we should not try too hard to interpret breccia formation as taking place under the conditions in the present-day asteroid belt. Here the lunar analogy, a motivation for this conference, proves valuable. The abundant annealed breccias from the lunar highlands are generally agreed to be the consequence of there having been a much more intense bombardment flux prior to ~3.9 b.y. ago than during subsequent time. The most obvious data supporting this are simply the ubiquitous ~3.9 b.y. ages found for these rocks by radiometric techniques. Although perturbations by younger events are discernable, no one would think of explaining the formation of these rocks by the present-day lunar bombardment rate.

Observation of other planetary surfaces, including the satellites of Jupiter and Saturn, show that intense bombardment during the early solar system was endemic, not a localized lunar phenomena. Measurements similar to those on lunar breccias have been made on the meteoritic breccias. The analogous ubiquitous age is 4.5 b.y. Therefore, it would seem just as incorrect to explain the formation of these breccias primarily in terms of the present-day asteroidal bombardment rates, solar-wind and flare fluxes, and galactic cosmic-ray irradiation. The effects of later events are certainly present, and are fundamental to the establishment of the asteroid-meteorite connection, but it seems just as certain that this is not the whole story. The brecciated meteorites have survived the past ~4.3 b.y. bombardment history more successfully than the lunar highland rocks. Several factors could contribute to their resilience. Probably the most important is that they are samples of the interiors of their ultimate parent bodies, not merely surface samples as returned from the moon. It is true, as pointed out by others (Housen and Wilkening, 1982), that the early system environment is very poorly known, and that the modeling of the formation of regoliths on present-day asteroids can be much more straightforward and quantitative. Again, nature has clearly issued the challenge to do something that will be difficult but important. Perhaps the most important application of models of present-day asteroidal regoliths will be their use in subtracting away more modern effects to reveal the primitive record.

In the foregoing, I have emphasized the asteroid-meteorite connection, best established for the differentiated meteorites and the ordinary chondrites. However, there is another possible meteorite source, the comets, for which a premature consensus would also be undesirable. Fireball studies (Ceplecha and McCroskey, 1976; Wetherill and ReVelle, 1982) show that there are objects entering the Earth's atmosphere from orbits very likely to be cometary, and with mechanical properties overlapping the weaker meteorites, e.g., C1 chondrites. These meteorites are also regolithic samples. Like the ordinary chondritic breccias they also bear the record of early solar system history. However, rather than rejecting a possible great opportunity, we should continue to examine the possibility that their record is that of a different place and possibly somewhat different time, that of the origin of comets.

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ABSTRACTS

OF KEYNOTE TALKS
& CONTRIBUTED ABSTRACTS

IMPACT DYNAMICS OF ASTEROIDAL BRECCIATION, Thomas J. Ahrens and John D. O'Keefe, California Institute of Technology, Division of Geological and Planetary Sciences, Pasadena, CA 91125.

We present a new framework for specifying the conditions required for asteroidal brecciation in terms of dynamic tensile (spall) strength of rock and projectile impact experimental data and numerical cratering calculations.

Recently Fujiwara(1) and Hörz and Schaal(2) have suggested that the major disruption mechanisms for much of the brecciation of asteroidal surfaces results from impact induced dynamic tensile failure especially on the rear or antipodal surface of the asteroid rather than a simple kinetic energy delivered to the rock criteria proposed by earlier workers.

Calculations of the attenuation of shock waves induced by impact of silicate and metallic impactors(3) and more recently water impactors of various densities (Fig. 1) when taken with the measurements of Fujiwara and Tsukamoto(4) suggest that three regimes of shock wave induced free-surface velocity attenuation take place in rocks. At distances varying from the impact point to 0.4 to $\sim$ 6 times the projectile radius (r) into the target, the near field regime, the spatial attenuation of peak stress in a target is low, the peak stress, P, is given approximately as

$$P \propto r^{n} \tag{1}$$

when $n \cong 0.2$ and thus the antipodal free surface velocity (V_E) of a nearly spherical object will be similar to impact velocity, V_I, or, $V_E = V_I$, in the terminology of Hartmann(5). At further distances, as described earlier by Ahrens and O'Keefe(3) stress amplitude decay and hence the resulting free-surface velocity of material at the antipode of an impact for a finite sized object depends strongly on projectile type and impact velocity. For rock and water impactors we have found that along the direction of impact, $P \propto r^{-n}$ in this second regime when n, varies with projectile velocity V_I as

$$n \cong -1.17 - 0.646 \log_{10} [V_I(\text{km/sec})] \tag{2}$$

where the attenuation coefficient of n = -1.0 is inferred to be appropriate for the elastic shock state(6), which for a basalt upon basalt impact will be $\cong$ 0.47 km/sec (Fig. 2).

Finally upon comparison of the free-surface velocity predicated at the antipode upon impact, measurements of the velocity of fragments ejected from the rear and side surface of basaltic targets by Fujiwara and Tsukamoto(4) define a third regime, which we designate the "late spall regime" (Fig. 3). For free-surface velocities above the stress levels of 1 to 2 kbar, corresponding to reflection of the initial stress wave, completely dynamic failure of the rock body in tension occurs(7). We thus infer that the impacts resulting in less than total destruction, are due to spalls which leave "core" of the object unbroken as in the experiments of Fujiwara and Tsukamoto(4) and Hörz(8). These interactions in which the free-surface velocity is far less than calculable using Eqs. 1 and 2 we define as the "late spall regime". Spalling in these interactions does not result from the initial wave interaction but is produced by latter, probably complex wave reflection at both the front (impacted) and rear (antipodal) target free-surface. The resulting brecciation is incomplete, and probably dependent in detail on the impactor and target and the interaction geometry.

IMPACT DYNAMICS OF ASTEROIDAL BRECCIATION

Ahrens, Thomas J. and O'Keefe, John D.

We conclude that basalt-like rock when exposed to stress wave reflections of 1 to 2 kbar, undergo dynamic tensile failure and complete brecciation. We infer that this stress level is an upper bound and larger prefractured objects may yield at even lower dynamic tensile strengths. The stress levels throughout an entire asteroid required to produce these stresses vary with impact or speed and mass. For example, for a 2.6 km/sec basalt impactor, the radius of the impactor need be only $\sim$ 10 to 15 times that of the asteroid to achieve total object brecciation. If the impact velocity of a basaltic object is controlled by the escape or gravitational infall velocity, objects having minimum diameters in the 10 to 30 km radius range will result in total in-situ brecciation upon gravitational infall of silicate objects of 0.05 to 0.1 times their mass.

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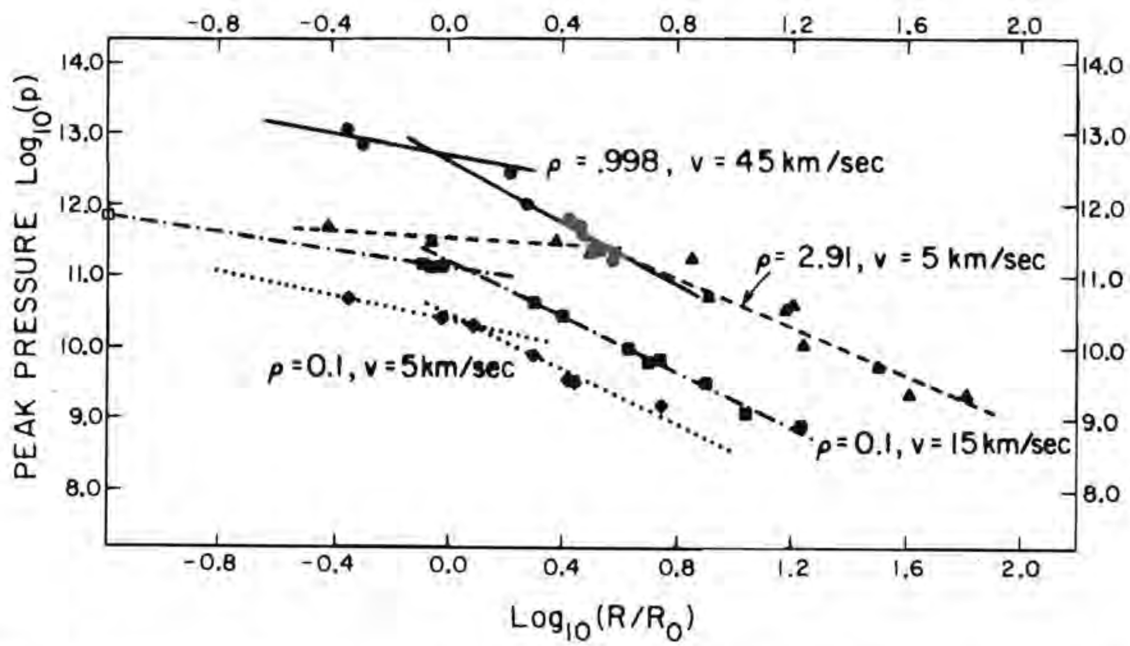

Fig. 1 $\mathrm{Log_{10}}$ peak center-line shock pressure, versus, $\mathrm{log_{10}}$ normalized radius for impacts of water and rock on rock (gabbroic anorthosite) target.

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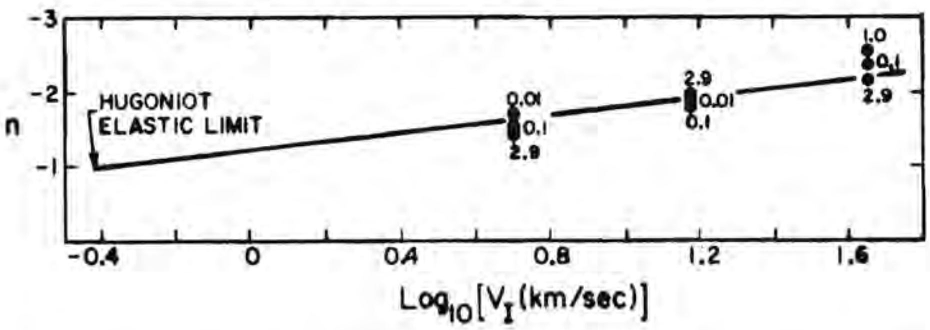

Fig. 2 Shock attenuation coefficient versus, impact velocity for far-field regime of Ahrens and O'Keefe (1977) for impact on gabbroic anorthosite target. Density values (g/cm^3) correspond to values of impactor.

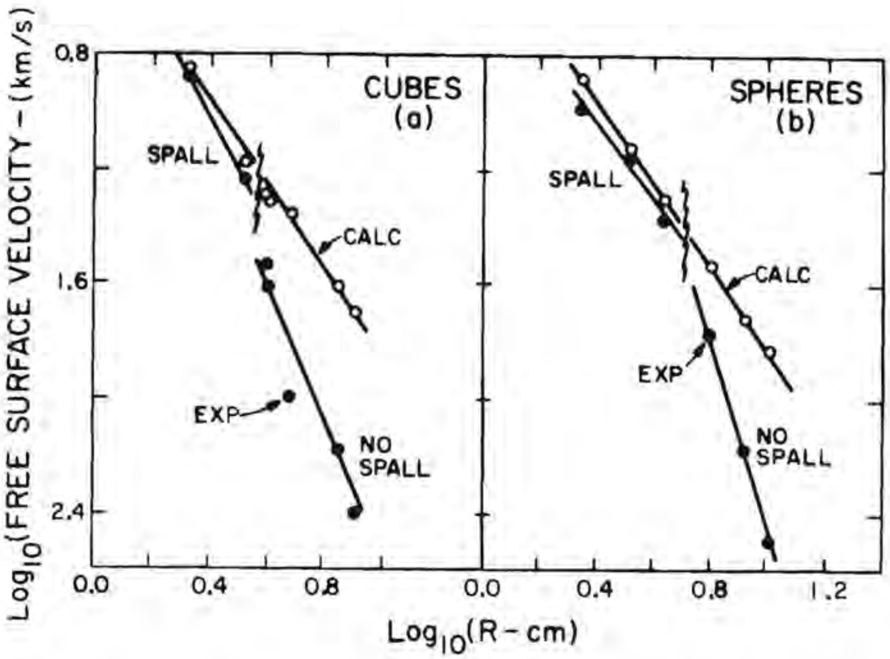

Fig. 3 Log_{10} free-surface velocity (km/sec), versus, log_{10} target thickness (cm), calculated from Eq. 1 and 2 for (a) impact into spheres, (b) impact into cubes. Data are from Fujiwara and Tsukamoto (1980). Break corresponds to 1 to 2 kbar dynamic tensile strength of basalt (Cohn and Ahrens, 1980) and approximately at the transition of complete break-up to "core" type break-up.

CHRONOLOGY OF BRECCIAS

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Breccias are rocks whose individual components may have experienced different and/or complex chronological histories. Breccias may be characterized by two general kinds of age events. One is the formation of individual components, usually by igneous or condensation processes; the second is brecciation and lithification as a result of collisional processes which may have partially or wholly reset the formation ages. Brecciation events may occur to individual clasts before incorporation into the breccia or to the breccia as a whole. Only chronologies based on decay of radioactive nuclides will be considered here. Some aspects of chronologies based on particle tracks will be given in the companion presentation by MacDougall.

An appreciable amount of thermal energy must generally be deposited into a rock to cause significant resetting of a radiometric parent-daughter system by solid state diffusion. The degree of resetting of isotopic ages by any event depends on such factors as the ease of diffusion of the particular elements, the nature and grain size of the mineral hosts, the amount of heat deposited in the rock (e.g., by shock waves), and the time required for the rock to cool. Available diffusion data suggests that, in general, noble gases and the alkali elements diffuse more readily than do alkaline earth elements, which diffuse more readily than rare earth (e.g., Nyquist et al., 1979). Very few direct studies exist, however, on the relative ease of resetting of radiometric systems in a given sample, and the results of these do not always appear consistent. More investigations in this area are needed.

Argon is a mobile element and is often lost during shock heating; therefore, the K-Ar system has been most often used in estimating times of shock degassing and breccia formation. Other radiometric systems (e.g., Rb-Sr, Sm-Nd, U-Pb) sometimes give times of shock heating and sometimes give pre-breccia formation ages of individual components. These last three techniques sometimes give information on formation times through the application of model ages, where certain initial parent-daughter relationships are assumed. Shock heating, however, usually only partially resets an isotopic system. Because of partial resetting and because disturbance of a radiometric system can be caused by factors other than collisional heating, it is not always possible to unambiguously identify a shock age or an original formation age from radiometric data on a shocked sample. For example, partial loss of radiogenic Ar or appreciable scatter in an Rb-Sr isochron plot may be due to several shock heating events, or it may be due to such things as chemical weathering, diffusion at room temperature, etc.

Cratering studies and radiometric dating of lunar, terrestrial, and meteoritic materials which have been subjected to a single impact process suggest that only a fraction of the impact-affected material will be heated sufficiently to cause resetting of ages (e.g., Grieve, 1980; Horz and Banholzer, 1980; and references below). To show appreciable resetting of ages, cratering ejecta must either be among the small fraction of material strongly heated, or be buried in a moderately hot ejecta blanket (or shocked object) which requires a long period of time to cool. Being involved in several cratering events would increase the probability of either of these conditions being true. Evidence for this assertion will be presented.

Ample evidence exists that some impact events can partially or wholly reset radiometric ages of rocks. Investigations of rocks from several terrestrial impact craters have shown K-Ar and Rb-Sr ages to have been partially or totally reset, depending upon the degree of shock heating (e.g., Wolf, 1971;

Hartung et al., 1971; Jessberger and Reimold, 1980; Jahn et al., 1978). Breccias returned from the heavily cratered lunar highlands commonly show radiometric ages between 3.8 and 4.1 Gy (e.g., Turner and Cadogan, 1975; Wetherill, 1975; Horn and Kirsten, 1976; Schaeffer and Schaeffer, 1977; Turner, 1977). The brecciated nature of these rocks, their older radiometric model ages, the existence of a few lunar rocks with ages > 4.1 Gy, and other evidence all indicate that the ages of these breccias are largely the consequence of impact resetting. Some investigators previously argued that the relatively tight clustering of ages among lunar highland rocks reflects the formation times of a relatively few large basin-forming events (e.g., Turner and Cadogan, 1975). More recently, several investigators have suggested that the much more abundant intermediate-size craters should also have reset chronologies, and that the cluster of highland ages may represent the end of a period of intense bombardment in which radiometric ages could have been partially or wholly reset many times.

Components of a given highland breccia need not all show the same age. Determination of K-Ar ages of 17 subsamples from breccia 73215 gave values between 3.92 and 4.28 Gy, many of which were resolvable from one another (Jessberger et al., 1977). The 3.92 Gy age of a partially melted felsite clast was inferred to be the brecciation age. These results imply that relatively small clasts escaped having their K-Ar ages totally reset by the Serenitatis event and that other highland breccias also contain components whose ages have not been reset totally by basin-forming events. Dating of individual clasts within highland breccias holds potential for a better understanding of old (> 4 Gy) ages. Dating of matrix and melted material within such breccias may give the best estimate of the brecciation event. Details of lunar chronology between 4.5 and 4.1 Gy ago are still largely unknown, but in principle could be better understood by additional dating on components of complex breccias with several techniques.

In contrast to early lunar history, cratering over the past ∿ 3 Gy apparently has not caused significant resetting of the ages of lunar rocks. Many recovered lunar rocks were either formed by lithification of the fine-grained regolith or were excavated from beneath the regolith by small- to medium-size cratering events during the past ∿ 2-500 My. In a few cases excavated rocks have had simple cosmic ray exposure histories and have been associated with specific craters. Nevertheless, most of these rocks show little or no resetting of their radiometric ages. In a few instances impact-produced glasses associated with rocks have been dated (e.g., see Kirsten, 1977) and give younger ages which presumably date glass formation. Most regolith breccias were not significantly heated during their formation, as attested by the high concentrations of solar wind gases contained in many of them. Radiometric dating techniques have not given the lithification time of regolith breccias although other evidence, including cosmic ray exposure ages, suggests that lithification of such breccias has been a continuing process. Because many of these breccias are made from lunar soil, individual particles (including glasses) can show partial resetting of ages because of a long history of impact events.

Several chondritic and achondritic meteorites with obvious evidence of having experienced shock and reheating show partial or complete resetting of radiometric systems as a result of that shock heating (e.g., Turner, 1969; Taylor and Heymann, 1969; Gopalan and Wetherill, 1971; Bogard et al., 1976; Bogard and Hirsch, 1980; Shih et al., 1981). The shock ages reported in these investigations are almost always considerably older than the collisional events which initiated the cosmic ray exposures of these meteorites. This can be interpreted by the earlier assertion that shock resetting of ages occurs either in a small fraction of ejecta or as a result of deep burial to retain shock-produced heat. Thus, the collisional events which initiate cosmic ray exposure of meteorites produce small bodies which cool quickly, whereas collisional events which have reset radiometric ages are in many cases associated with physical evidence of appreciable heating (sometimes in excess of 800°C), and have often been interpreted as having resulted in thick ejecta and slow cooling (e.g., Taylor and Heymann, 1971; Smith and Goldstein, 1977; Bogard and Hirsch, 1980).

The meteorites mentioned above, although shocked, are not breccias in the strict sense. Many meteorites, however, are breccias which apparently formed by lithification of fragmental material on their parent body. Radiometric dating has been reported for several of these (see Kirsten, 1977, and Bogard, 1979, for summary listings). Most measurements of whole rock or matrix material of these breccias indicate disturbance of radiometric systems in the time period of $\sim$ 3-4.4 Gy ago, but it is generally not possible to assign specific event ages. Age determinations have been possible for individual components in a few brecciated meteorites, however. Two clasts from the Kapoeta howardite gave K-Ar or Rb-Sr isochron ages of $\sim$ 3.5-3.9 Gy, whereas a third clast gave ages of 4.5-4.6 Gy (Rajan et al., 1979). A shock remelted fragment from the Plainview H5 chondrite gave a K-Ar plateau age of 3.6 Gy, whereas the host suggested ages up to 4.4 Gy (Keil et al., 1980). Both Kapoeta and Plainview contain trapped solar wind gases, and Plainview contains volatile-rich carbonaceous components. It would have been impossible to have reset the ages of clasts in these meteorites after breccia formation without resetting the entire breccia. Both of these breccias must have formed more recently than 3.5-3.6 Gy ago, which demonstrates that well-developed regoliths existed on the parent bodies of howardites and H-chondrites at least this recently. Additional chronological evidence for meteorite breccia formation also exists. Glass from the Bununu howardite, which contains solar gases, gave a K-Ar age of 4.2 Gy, whereas a feldspar separate was dated at 4.4 Gy (Rajan et al., 1975). Shocked feldspar and glass from the Cachari eucrite was interpreted to represent an event 3.0 Gy ago (Bogard et al., 1981). Glass and a separated clast from the heavily shocked Malvern howardite gave K-Ar ages of 3.6-3.7 Gy (Kirsten and Horn, 1975; Rajan et al., 1975).

Two important questions are whether these ages determined on components of meteorite breccias are related to the cataclysmic bombardment of the Moon and whether meteorite breccia formation has occurred in geologically recent times. The answer to the former question is unknown. Two studies on cosmic ray exposure of individual chondrites indicate that the answer to the latter question is yes. One inclusion out of 7 in the Weston H chondrite had a 20% longer exposure age (Shultz et al., 1972), and a particle track study of 12 inclusions in the Djermaia H condrite revealed differences in irradiation conditions (Lorin and Pellas, 1979). As chondrite exposure ages are of the order of 10 My, these results suggest the existence of regoliths and brecciation events this recently.

Two classes of achondrites which may be genetically related show young ages by a variety of radiometric techniques. Three known Nakhlite achondrites, unshocked meteorites which formed by crystal-liquid separation, give essentially identical formation ages of 1.3 Gy by the K-Ar, Rb-Sr, U-Pb, and Sm-Nd dating systems (see Bogard, 1979; Nakamura et al., 1981). K-Ar, Rb-Sr, and Sm-Nd determinations on two shergottite achondrites and a third related meteorite suggest igneous formation $\sim$ 0.9-1.3 Gy ago (Shih et al., 1981). These meteorites were shocked $\sim$ 0.18 Gy ago, which resulted in the partial or complete resetting of several isotopic systems. How and where these achondrites formed so recently in solar system history is an important question. Although none of these meteorites are breccias, the possibility that they formed from igneous processes resulting from intense collisional melting must be considered.

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PROPERTIES AND DYNAMICS OF ASTEROIDAL REGOLITHS AND THE RELATION TO ACCRETIONARY PROCESSES; C.R. Chapman, Planetary Science Institute, L.L. Wilkening, Lunar and Planetary Laboratory, University of Arizona 85721

Observed Properties of Asteroids. Zellner summarized for the workshop the available evidence about the physical nature of asteroids. The remote-sensing techniques measure only the surfaces or uppermost surface layers of asteroids, so that information about interiors is only inferential. Polarimetry demonstrates that asteroids have dusty surfaces, similar to dust-covered rocks. Infrared measurements indicate that asteroids including bodies as small as 433 Eros, have a thermally insulating layer at least a centimeter thick. Radar measurements are capable of probing still more deeply into asteroids, but the implications of the recently obtained data are still not fully understood. Asteroids appear "rough" to radar, but it cannot be easily determined whether the scale of roughness is on the meter scale or on the scale of the body itself (kilometers). The data have been interpreted as being compatible with regoliths.

Observations of asteroids as they rotate indicate that individual bodies have a high degree of compositional homogeniety. Any changes in color, albedo, spectrum, etc. observed as different hemispheres rotate into view are small or absent. Whether this means that an asteroid is compositionally homogeneous, or simply that ejecta from the last large crater has blanketed the body with material from a single location, cannot be determined. Hirayama families are groups of asteroids believed to be fragments from precursor bodies involved in a supercatastropic collision. Impact probabilities would imply that most fragments are due to the largest body. Most of the large fragments have similar spectra, consistent with the idea that the precursor body was of homogeneous composition throughout its bulk. Some smaller families, however, show great compositional diversity implying that the precursor body was geochemically differentiated. (Perhaps the smaller families are somehow "unreal" despite the formal statistical estimates that they cannot be due to chance.)

Various observations indicate that asteroid surfaces do not undergo the same kind of optical maturation as is observed for the moon. Whether this is due to differences in the impacting environment (e.g. lower impact velocities in the belt) or reflects different compositions, that respond differently to the processes of maturation, is not known.

Recent work reported by Zellner and his associates (1981) has identified a striking pattern of compositions of main belt asteroids as a function of distance from the sun. It had been known before that the so-called S-types, which may be ordinary chondrites, although stony-irons and disrupted/reassembled achondrites cannot be ruled out, predominate in the inner asteroid belt while the black C-types thought to be of carbonaceous composition dominate in the outer half of the belt. In addition to these trends, Zellner reports that the rare E types occur at the inner edge of the main belt and that the M-types predominate in between the maxima in the distributions for S and C. Furthermore, a new type designated "P" is populated only near the outer edge of the main belt and beyond while the "D" types are most common among the Trojans, far beyond the main belt.

Thus there is a systematic ordering of asteroidal materials with distance from the sun. Whether this reflects primordial compositions or subsequent processes of implantation or evolution of asteroids is not yet known.

Dynamics of Regoliths and Megaregoliths. The development of regoliths on asteroids, i.e., meteorite parent bodies is different from the well-studied case of the lunar maria for several reasons. The impacting flux of projectiles is greater within the asteroid belt than on the moon. But, most important, the lower gravity on asteroids results in much more widespread distribution of ejecta. Lower gravity also results in appreciable loss of ejecta from smaller asteroids. Asteroidal surface material is either buried or ejected resulting in less re-working than on the lunar surface. Furthermore, asteroids may be entirely broken up by large catastrophic collisions; the pieces may reassemble to form a new body that is composed of megaregolith throughout, or the pieces may fly apart permanently.

Several features of the impact environment in the asteroid belt serve to modify the importance of processes associated with regolith evolution on the lunar surface. For instance, there is a smaller percentage of micrometeoroids (e.g. of cometary origin) relative to big projectiles in the asteroid belt compared with the lunar environment. Combined with the overall lower average impact velocities in the belt, one expects formation of fewer agglutinates, microcaters, and less comminution of small particles relative to effects due to large events.

At present there is relatively poor understanding of the physical effects of large impacts on the character of regoliths. Among the poorly understood effects and parameters are crater size scaling, the impact energy necessary to fracture an asteroid, the importance of spallation of surface layers as a response to a large impact, the degree of shock comminution of the interior of an asteroid, and processes of lithification.

One major area of uncertainty relates to the impact flux in the asteroid belt. The number of asteroids smaller than 10 km diameter is poorly known, and there is essentially no information about the population smaller than 1 km diameter down to centimeter-scale meteoroids. Comparisons of the impacting fluxes on the moon and asteroids, reported by Shoemaker, suggest that there has been only about a 6-fold higher cumulative cratering rate on the larger asteroids compared with the moon (not considering possible higher fluxes in one or both locations in the past). This estimate is lower by one-half to one order of magnitude than the fluxes used by earlier workers. The problem was not resolved at the Workshop, although it was agreed that there is a paucity of data available to answer the question definitively.

Models developed by Langevin and his co-workers and by Housen and his colleagues are in fairly good agreement about the nature of regolith development on asteroids. Disagreements are never more than a factor of a few (in total regolith depth, for instance) and relate primarily to differences in modelling ejecta velocity distributions. Both groups agree that episodic blanketing of asteroid surfaces by widespread ejecta results in less reworking than occurs on the moon. Thus asteroidal regoliths are deeper, coarser, and individual grains are only rarely exposed at the surface. These model predictions are in good agreement with the qualitative differences between meteoritic and lunar regolith breccias (lower track densities, lower gas contents, larger particle sizes, etc.). Quantitative comparisons of meteorites with the models are limited by uncertainties in the input parameters. In addition, as Housen emphasized, the inherently stochastic nature of the regolith-development process results in uncertainties of a factor of a few just due to random chance.

Neither the Housen nor Langevin models treat the complicated question of megaregolith development. There is good reason to believe that asteroids are fragmented (and reaccumulate) on timescales shorter than the age of the solar system. This idea, which has been advocated by Davis, Chapman, and others, is now gaining some support from meteoritical studies. For example, Rubin et al. (this volume) presented evidence concerning the cooling histories of ordinary chondrites that point in the direction of disrupted and reassembled chondrite parent bodies. The different cooling rates found in single meteorite samples seem to require that materials that evidently cooled slowly at depth have subsequently been rearranged and located in a near-surface environment to become converted into a regolith breccia.

One important area of study that has been largely neglected so far concerns the early history of regolith development in the asteroid belt, e.g., in the earliest accretionary epochs or during subsequent transitional epochs prior to, and during, the late-heavy bombardment epoch in planetary cratering history. The Langevin and Housen models (see abstracts in this volume) could be studied with a range of input parameters appropriate for different models of planetesimal populations or earlier asteroidal populations. This has not yet been done. One must be careful, however, in piling too many uncertainties on top of one another. Already in the case of the modern-day solar system, there are many parameters that are poorly understood.

Related to the regolith evolution models are some recent studies that attempt to link asteroid parent bodies with meteorites. Chapman described recent work by himself and Greenberg that considers the collisional evolution of asteroids and resulting body strengths of asteroids as a fundamental input to their model of meteorite production. They suggest that large cratering events liberate most meteorites from parent-bodies; the highest velocity ejecta most readily escape and reach resonances capable of transferring them into Earth-crossing orbits. In the Greenberg-Chapman model, the smaller asteroids are especially weakened by processes of disruption and reassembly and megaregolith formation; therefore, meteorites are preferentially derived from larger, stronger bodies.

Accretionary Processes. Regolith models have been quite successful in explaining the appearances and radiation histories of most brecciated meteorites. The regolith models are based on collisional processes, and as pointed out at the beginning of our summary, it should be recognized that their predictive and explanatory power is limited solely to the post-accretion era. One of the motivations for devising such models was to be able to disentangle the effects of collisions from those of earlier processes which operated to form meteoritic matter and the parent bodies. In particular one hoped to be able to identify the effects of accretion in primitive meteorites, especially the ordinary and carbonaceous chondrites.

Gas-rich ordinary chondrites are similar to gas-rich achondrites in all the features that lead to the appellation gas-rich. This includes abundances of noble gases, maximum observed solar flare track densities percentage of solar flare irradiated grains, and occurrence of solar flare track density gradients. Hence, it seems that a common set of processes, as modeled, can account for both the ordinary chondritic and achondritic gas-rich meteorites.

In the case of carbonaceous chondrites (CI's and CM's) the mineralogy is largely a product of aqueous processes which must have taken place in the parent body and may or may not have been contemporaneous with brecciation processes. Because of this carbonaceous chondrites cannot be explained solely as products of condensation and accretion modified by brecciation and comminution as can the ordinary chondrites and achondrites. There are also problems explaining the radiation history of carbonaceous chondrites. Carbonaceous chondrites have very short ($\lesssim 10^6$ yrs.) cosmic ray exposure ages. For some meteorites the recent exposure as measured by ^{26}Al is the same integrated exposure as measured by ^{21}Ne. This implies that the exposure the material received in the parent body regolith must have been less than the marginally measurable difference between the two ages. As the ages are accompanied by rather large uncertainties, in practice this means in most cases that the parent body exposure could really be 10^5-10^6 yrs. This fits into regolith models, but just on the ragged edge.

The qualitative differences between the irradiation records of gas-rich carbonaceous chondrites and other gas-rich meteorites are more difficult to account for than the exposure ages. In fact, carbonaceous chondrites were not included among gas-rich meteorites for many years because their relatively lower contents of Helium-4 and ambiguous neon isotope ratios did not make them as easily recognized as gas-rich by these two traditional criteria as other gas-rich meteorites. When the solar flare particle track records were studied, it was found that they too differed from those of other gas-rich meteorites. The total track densities were lower and fewer grains showed gradients in density on one side or on more than one surface. It appears that on the average the carbonaceous chondrites experienced less exposure at the very surface of the meteorite parent body. Or in other words, the average material we have to study was more shielded in its parent body environment.

Explanations, which have been put forward for the differences, fall into two groups: (1) those calling on the low strength of carbonaceous materials to account for a different response of the weak carbonaceous chondrite parent bodies to the collisional environment of the asteroid belt; (2) the suggestion that the carbonaceous chondrites were irradiated in the early solar system as decimeter-to-meter size bodies prior to accretion (Goswami and Lal, 1979). The carbonaceous chondrites remained an enigma at the conclusion of the workshop.

On the basis of the understanding of regolithic processes that was achieved, it was agreed at this meeting that we can identify some components in chondrites which are not products of collisional processes on meteorite parent bodies. For the first time a concensus developed that chondrules predate the collisional processing of asteroidal material. Chondrules then join Ca, Al-rich inclusions (CAI's) as primordial chondritic constituents that accreted to form meteoritic parent planets.

In conclusion, it seems the models of regolith evolution show that collisional processes must have had a significant effect on the surface materials on small bodies. A thorough study of the lunar samples and meteorites has shown that although brecciation and comminution processes operated on meteoritic parent material, the collisional environment in which meteorites formed was milder than the moon's. Most meteorites show lesser effects of collisional melting and comminution than do lunar soils and breccias. The regolith models show, in fact, that blanketing by successive layers of regolith protect newly formed regolith until its ejection. An additional mechanism for protecting brecciated asteroidal material from further processing might be deep burial as a result of catastropic fragmentation and gravitational reassembly of the parent body.

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PRISTINITY PROBLEMS ON A BASALTIC ACHONDRITE PARENT (BAP): CHONDRITIC CONTAMINATION OF BASALT CLASTS FROM POLYMICT EUCRITES.

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INTRODUCTION: Lunar samples have long been known to be contaminated, by varying amounts of meteoritic projectile material (Wasson and Baedecker, 1970), and the search for 'pristine', uncontaminated lunar samples continues to the present (e.g. Warren and Wasson, 1980). The basaltic achondrites, however, have been generally assumed to be uncontaminated. Recent data suggest that this assumption may not be true for some clasts from polymict eucrites. The discovery of polymict eucrites in Antarctica (Miyamoto et al., 1978) has increased the diversity of samples of the basaltic achondrite parent (BAP). Basaltic clasts from polymict eucrites are generally similar to those from howardites (Delaney et al., 1981b) but the proportion of unequilibrated to equilibrated basalt clasts (Reid and Barnard, 1979) is much higher. The unequilibrated clasts have variolitic to subophitic textures characteristic of rapid subliquidus cooling (Lofgren, 1977; Powell et al., 1980). Pyroxene in unequilibrated clasts from ALHA78040, EETA79004 and EETA79011 has variable Fe-Mg-Ca zoning and very thin Ca-rich exsolution lamellae (Delaney et al., 1981a). These clasts were not held at a high temperature long enough to allow chemical homogenization and they therefore differ from most monomict eucrites, many mafic clasts from howardites and some pyroxene-bearing clasts in polymict eucrites. The lack of clouding in the unequilibrated clasts (Harlow and Klimentidis, 1980; Harlow and Delaney, 1981) also indicates that they are unmetamorphosed. The chemical composition of many clasts extracted from the polymict eucrites suggests that they sample a source different from the main portions of their host meteorites (Wooden et al., 1981; Smith and Schmitt, 1981).

PETROGRAPHIC EVIDENCE: Variolitic, spherulitic and fine grained porphyritic basalts in both Allan Hills and Elephant Moraine polymict eucrites formed as a result of rapid cooling. Circular glass clasts (EETA79004,32: EETA79005,41) and pyroxphyric basaltic glass clasts (EETA79005,40) showing incipient devitrification attest to rapid quenching. The circular glass clasts must have been ejected forcibly from a planetary surface by either vigorous volcanic activity or an impact melting event. The survival of these clasts as glass indicates that they were incorporated into a cool regolith. The presence of broad exsolution lamellae and clouding, the absence of zoning in pyroxene from both lithic and mineral clasts, and pyroxene-matrix relationships (Fuhrman and Papike, 1981) in the same regolith indicates that parts of that regolith had been previously metamorphosed. In EETA79004 and EETA79011, the nearly uniform pyroxene composition in most clasts suggests that, except for the rare unequilibrated clasts, these two regolith samples were metamorphosed in their present state. The unequilibrated and glassy clasts were, therefore, late, post-metamorphic additions to the regolith. The unequilibrated basalt clasts in polymict eucrites tend to be larger than most other clasts suggesting that they suffered less comminution than the other clasts. This is also consistent with their late addition to the regolith. These basalts should, therefore, have formed because of late vulcanism or impact generated partial melting.

CHEMICAL EVIDENCE: The chemical analyses of separated basalt clasts from polymict eucrites reveal distinct differences between these clasts and their host eucrites (Wooden et al., 1981; Smith and Schmitt, 1981). Alkali enrichment

in some clasts may be interpreted as the result of different crystal-liquid separation histories from the monomict eucrites. Grossman et al. (1981) describe one large clast (#4) from ALHA76005 that has unique oxygen isotopes plotting between the basaltic achondrite fractionation line and the ordinary chondrite ^{16}O mixing line (Clayton et al., 1979). Grossman et al. showed that bulk ALHA76005 cannot be derived from clast #4 by mixing C2 chondrite into the achondritic matrix. An alternative hypothesis, that clast #4, but not the bulk meteorite, was contaminated by O-chondrite should be considered. The oxygen, three-isotope diagram of Clayton et al. (1979) with the projections, H' and L', of H and (L+LL) chondrites respectively through clast #4, onto the basaltic achondrite fractionation trend is shown (Fig. 1). H' and L' represent lever rule controlled compositions needed to create clast #4 by mixing O-chondrite with achondrite. Both H' and L' fall within the range of known basaltic achondrites. The oxygen in clast #4 may, therefore, be treated as a mixture of ordinary chondrite and basaltic achondrite oxygen. Lever rule considerations make L or LL chondrite a more attractive mixing component since the bulk oxygen of clast #4 would contain less chondritic contamination than if H-chondrite is mixed in. Further evidence of chondritic contamination in clast #4 may be derived from the trace element data of Grossman et al. (1981). In Table 1 concentrations of several trace elements are listed for average eucrite, Moore County (to which clast #4 shows compositional similarity), L+LL chondrite and ALHA76005 clast #4. The siderophile content of clast #4 is higher than most eucrites but is consistent with contamination by chondritic metal. Mixing of other trace elements and major elements from eucrites and chondrites provides variable ratios of achondrite:chondrite in clast #4 but crystal-liquid separation may have complicated the interpretation of these data.
DISCUSSION: ALHA76005, clast #4 (Grossman et al., 1981) shows evidence of chondritic contamination and hence, probably formed in an impact-melting event rather than by indigenous igneous activity. Compositional trends defined by similar clasts from polymict breccias may reflect the ratio of components in pre-impact breccias rather than igneous crystal-liquid trends. Extreme caution is therefore urged in the interpretation of achondritic 'fractionation' trends. The clear analogy between the evolution of a BAP regolith and the intensively studied lunar regolith with its familiar contamination is, therefore emphasized. The variability of Rb-Sr and Sm-Nd ages (4.6-4.44 Ga) (Wooden et al., 1981) may reflect resetting of isotopic clocks on a BAP crust, perhaps as a result of some event like the terminal lunar cataclysm (Tera et al., 1974). If the younger ages date impact events on BAP, then the metamorphism that influenced many clasts in the chondrites must have occurred within the first 200Ma of the solar system.
CONCLUSIONS: (1) Some unequilibrated basalts and glassy clasts in basaltic achondrites were produced by the impacts of ordinary chondrite projectiles on BAP. (2) Contamination of the clasts by chondritic oxygen, and especially siderophile trace elements, can be identified and may provide a method of distinguishing between pristine and contaminated basaltic achondritic material. (3) The effects of impact melting a howarditic or eucritic breccia may produce spurious igneous trends in contaminated achondritic data sets. (4) Identification of pristine BAP material is important to further understanding of this body. Contaminated material may provide useful information about the projectiles (e.g. from siderophile/Ir ratios). (5) Some chondritic bombardment of the BAP regolith post-dated thermal metamorphism and its associated homogenization. (6) Separate parent bodies are not needed to explain differences between clasts and bulk polymict eucrites. (7) Detailed studies of BAP reveal complexities and variability directly analogous to the moon.
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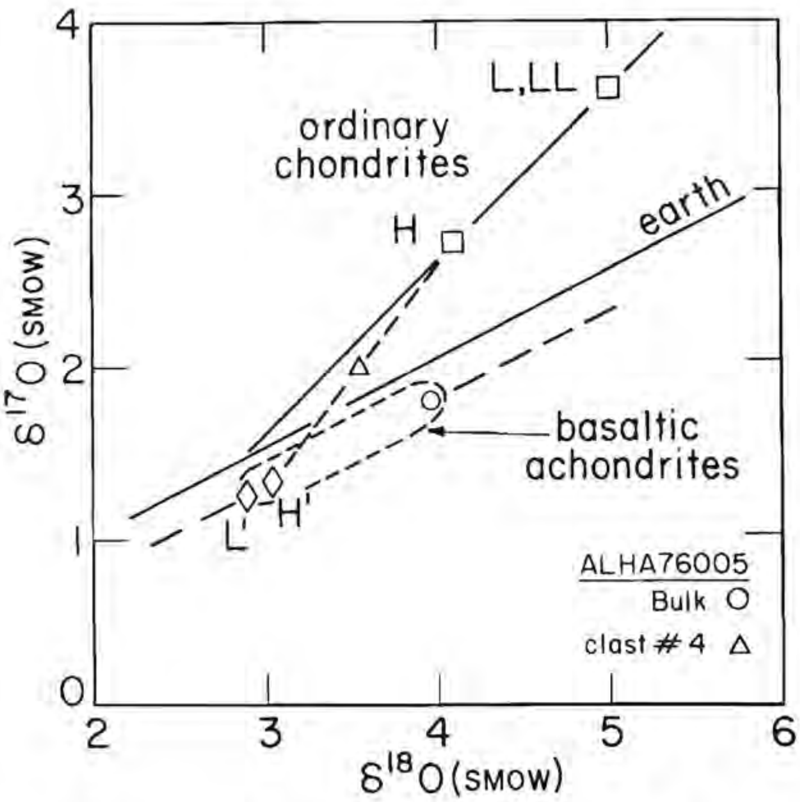

Fig. 1. Oxygen, three-isotope plot after Clayton et al., (1979) with ALHA76005 clast #4 shown as a mixture of basaltic achondrite (either L' or H') with ordinary chondrite L, LL or H. Construction line is shown only for H-chondrite.

Table 1: Trace elements in ALHA 76005 clast #4, average eucrite, Moore Co., and typical L and LL chondrites (all units ppm)

	Moore County	average eucrite	clast #4 A76005	L+LL chondrites
Co	3	5.8	17.3	400-650
Ni	3.5	8.3	440	$>10^4$
Ce	3.1	8.3	3.2	1
Eu	0.59	0.67	0.457	0.08
Au	0.23		2.5	110-220

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SPECTRAL VARIATIONS ON ASTEROIDAL SURFACES: IMPLICATIONS FOR COMPOSITION AND SURFACE PROCESSES. M.J. Gaffey, T. King, and B.R. Hawke, Planetary Geosciences, Hawaii Inst. of Geophysics, Univ. of Hawaii, Honolulu, HI 96822; M.J. Cintala, NASA Johnson Space Center, Houston, TX 77058

Introduction: On solid solar system objects, the geologic history of the object has been recorded in terms of lateral variations in the composition, mineralogy, and petrology of surface and subsurface units, their stratigraphic relationships, and the morphology of exposed surfaces. Recently, an observational program was initiated at the University of Hawaii to obtain high precision 0.3-2.5 μm reflectance spectra for many short intervals over the rotation period of a number of selected asteroids which have been shown to exhibit light curves with non-shape related variations. The purpose of rotational spectral studies is to determine the mineralogy, petrology, and lateral extent of units on the surfaces of asteroids in order to provide an improved understanding of their composition and surface processes, and hence to shed light on the origin and evolutionary history of an important class of solar system objects.

Asteroid Rotational Spectral Variations: High photometric precision spectral and rotational studies of asteroids have been carried out on the U of H 2.2 meter and NASA Infrared Telescope on Mauna Kea. Both two-beam photometer (0.3-1.1 μm) and CVF spectrometer (0.6-2.5 μm) rotational spectral data have been collected. The preliminary results for 4 Vesta, 6 Hebe, 1 Ceres, and 2 Pallas were presented by Gaffey[5,6]. The initial results for the sixteen objects so far observed as well as additional information are presented in table 1.

Where sufficient rotational coverage was obtained, most of the observed bodies exhibit rotational spectral variations which indicate the existence of mineralogically distinct provinces on their surfaces. In this observational program, a rotational spectral variation must exhibit reproducible spectral changes with identical magnitude and rotational phase relationships on at least two different nights in order to be considered 'definite'. Variations which are significantly larger than the internal errors of the observations but for which insufficient observations (e.g. only a single night) are available are rated as 'probable'.

Definite or probable rotational spectral variations have been found associated with asteroids which exhibit a wide range of diameters (68 km - 957 km) as well as types (C, S, M, E, R, and U). Two general modes of rotational spectral variation have been identified. The first can be demonstrated to be due to sharply bounded features. The second type is more gradational in nature and appears to reflect hemispheric compositional differences. Although the spectral variations are often subtle (i.e. only a few percent deviations from the mean), the mineralogic and petrologic surface heterogeneity which these indicate is often major (i.e. spanning an entire suite of meteoritic assemblages).

6 Hebe exhibits hemispheric variations of about 5-10% in the relative abundance of olivine, pyroxene, and metal. The pyroxene compositions are not consistent with an undifferentiated chondritic assemblage. The surface mineral abundances exhibit a complex spatial variation and at least one sharply delineated feature has been detected.

4 Vesta exhibits variation in the pyroxene absorption band depths of about 7% as well as shifts in absorption band position (∿100Å and ∿700Å respectively for the 1 & 2 μm bands) with rotation. Our 0.33-1.0 μm spectral measurements cover ∿65% of a rotational period and the 0.7-2.5 μm data cover 2.5 rotation periods. This data shows a ∿2% variation in relative reflectance near 0.35 μm which is consistent both in magnitude and sense with the results of Stephenson[14], Gehrels[7], and Blanco and Catalano[1]. Both the variations in band depth

and band center are significantly greater than the upper limits reported by Feierberg et al.[4]. At least one small feature in the lightcurve--a ~1% 'bump' just after minimum light--appears to correlate with a significant decrease in the depth of the short edge of the 1 μm band, indicating a 'spot' deficient in low-Ca pyroxene.

Comparison of the plagioclase band depth variations to those of the pyroxene does not reveal either a simple direct or inverse correlation. If the variation in band intensity were produced by regional grain size variations, geometric scattering effects (body shape), or the addition of an opaque phase, one would expect a positive correlation. The absence of an inverse correlation suggests that the band depth variations are not the result of variations in the relative abundance of two phases of constant composition. The complex nature of the actual band depth correlation plot along with significant variations in pyroxene chemistry indicate that the surface material of Vesta is not homogeneous even on a scale significantly smaller than a hemisphere and that the surface consists of mineralogic units spanning the range of the basaltic achondrites.

1 Ceres and 2 Pallas exhibit 0.33-2.5 μm spectral curves unlike any known meteorite type, and which indicate the absence of significant oxidized iron in silicates and the lack of detectable organic carbon compounds in the surface materials of these asteroids. The most probable surface assemblage for these objects would be a magnetite + iron-poor phyllosilicate mixture which could be produced by aqueous alteration of C1-C2 material. Some spatial spectral variation appears to be present on the surface of Ceres but sufficient rotational coverage does not yet exist for Pallas.

3 Juno exhibits 0.3-1.1 μm spectra which show that both the blue (0.40/0.56 μm) and red (0.90/0.56 μm) portions of the spectrum appear brighter at maximum light[3]. Three possible surface material variations could produce such an effect: 1) a decrease in olivine abundance, 2) a smaller mean particle size, or 3) the presence of a less Fe-rich olivine.

349 Dembowska also exhibits rotational spectral variations. The 0.3-1.1 μm spectra obtained for Dembowska show an infrared (0.90/0.56 μm) variation of 4%.

In addition, color variations have been reported for 71 Niobe, 944 Hidalgo, and 433 Eros[3,12,13].

Processes Responsible for Spectral Variations: Preliminary Assessment: It seems likely that the rotational spectral variations described above are related to the accretional, thermal, and impact histories of the asteroid parent bodies. In many instances, a complex combination of processes may have been operative. A major task for future work will be to use the nature of the spectral differences to unravel the complex surface histories of the asteroids.

1. Accretional heterogeneity - It seems likely that original accretional surface heterogeneities would have been destroyed by impact and other processes. Widespread ejecta distribution and mixing from multiple impact events would generally act to homogenize asteroidal surfaces. Repeated impact into an undifferentiated asteroid should produce a surface with very minor hemispheric compositional differences. The situation is complicated by differentiation processes and by impacts of sufficient energy to cause catastrophic disruption of the parent body. Re-accretion of disrupted parent bodies could yield new bodies with initially diverse surface compositions. Hartmann[9] demonstrated that low-velocity collisions between comparable-sized asteroids could result in elongated asteroids with diverse surface compositions.

2. Impact processes - The most profound effect of energetic impact is catastrophic disruption. Some of the resulting collisional fragments could reflect internal compositional variations. As discussed above, re-accretion

of these fragments could result in a body with a variable surface composition. A common impact effect (Cintala et al.[2]) would be the exposure of material from the interiors of asteroids. This effect would be more pronounced on those bodies that were differentiated or thermally metamorphosed. Although the ejecta of a given impact may totally cover the surface of an asteroid, material from deeper layers should be more abundant near the parent crater and major surface compositional differences could be created.

Impact melt would be generated during high-velocity impact events on asteroidal surfaces. Although simple cratering calculations suggest that molten material would be totally lost because it had been subjected to higher shock pressures and hence should have had higher post-shock particle velocities, studies of crater deposits on the Earth, Moon, and Mercury[10,11] have demonstrated that major quantities of melt exist in and around craters on these bodies. Apparently, some melt is driven downward in the expanding crater cavity and is either ejected very late in the event or not at all. Therefore, impact melt bodies should also be present on asteroidal surfaces. Probable impact melt deposits have been identified associated with fresher, less degraded craters on Phobos[8,16]. Three points should be emphasized. First, the volume of melt produced for an impact crater of a given diameter on an asteroid will be much smaller than for a similar sized crater on the Moon or Mercury. Second, differentiation of the melt body is unlikely. Differentiated impact melt bodies have not been identified on Earth and the low gravity prevalent on asteroids makes crystal settling even more unlikely. Three, it is likely that melt deposits on most asteroids would exhibit spectral differences relative to the bulk surface composition.

3. Endogenic processes - A variety of endogenic processes could operate to produce surface compositional variations. Thermal metamorphic effects, regardless of source, could be exposed by impact processes. Volcanic flooding by magmas of various compositions could be detected by current remote sensing techniques. Vesta appears to have a surface composed of diverse extrusive flood basalt flows. Takeda[15] has proposed a model which is consistent with the currently available observational data.

Table 1: Objects Observed

Asteroid	Diameter (km)	Type	No. of Obs. Runs	Rot. Cov. on Each	Spectral Variation
1 CERES	957	C	4	10%, 10%, 100%, 20%	Probable
2 PALLAS	538	U	2	30%, 15%	Possible
3 JUNO	267	S	2	65%, 200%	Yes
4 VESTA	555	U	4	60%, 100%, 65%, 200%	Yes
6 HEBE	206	S	3	100%, 200%, 50%	Yes
7 IRIS	222	S	1	150%	Probable
9 METIS	168	S	1	100%	UNREDUCED
15 EUNOMIA	261	S	1	50%	Probable
16 PSYCHE	249	M	2	60%, 150%	Probable
19 FORTUNA	226	C	1	25%	UNREDUCED
29 AMPHITRITE	199	S	1	70%	NONE SEEN
44 NYSA	68	E	1	100%	Probable
51 NEMAUSA	156	U	1	60%	Possible
52 EUROPA	292	C	1	—	UNREDUCED
349 DEMBOWSKA	149	R	2	150%, 150%	Yes
511 DAVIDA	335	C	1	15%	Possible

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CONSTRAINTS ON THE IRRADIATION HISTORY OF THE GAS-RICH METEORITES: J.N. Goswami[1] and K. Nishiizumi[2], [1]Physical Research Laboratory, Ahmedabad-380009, India; [2]Dept. of Chemistry, Univ. of California, San Diego, Calif.-92093, USA.

The qualitative similarity in the solar wind and solar flare irradiation records in lunar soils and gas-rich meteorites and the presence of impact microcraters, glassy spherules and probable agglutinates in both these sets of samples have led to a general consensus that the gas-rich meteorites are regolith breccias, and that the observed irradiation features in them are produced during their exposure in the asteroidal regoliths (Rajan 1974 and references therein). Attempts to characterize the impact processes operating in the asteroidal regoliths, based on correlation studies of cosmogenic records in lunar soils and in gas-rich meteorites (Anders 1975, 1978; Price et al. 1975), indicated that the flux of impacting objects on the asteroidal regoliths must have been orders of magnitude higher compared to that on the lunar regolith, and that the regolith growth on asteroidal bodies is predominantly accretionary in nature with very little gardening or mixing of the upper layers. This simplistic picture of regolith irradiation scenario for the gas-rich meteorites, however, suffers from two severe drawbacks. First, the wrong use of total cosmogenic exposure age as the regolith exposure duration, T_R, and in some cases use of T_R as a free parameter, in the analyses made to reach the above conclusions. Second, the failure to match the abundances of gas-rich members among different types of meteorites on the basis of analytical modelling of the dynamical growth and evolution of asteroidal regoliths (Housen et al. 1979; Langevin and Maurette 1980).

Goswami and Lal (1979) have pointed out that in the case of CI and CM chondrites, the regolith irradiation duration, more appropriately termed as pre-compaction irradiation duration, T_{PC}, is extremely short ($<10^5$ yrs). They have also discussed in detail why such short time scale is not compatible with the observed solar flare irradiation records in these meteorites, if one considers the regolith irradiation scenario, and proposed that the irradiation records in them can be better explained if one postulates that the irradiation took place prior to the formation of the parent bodies of CI and CM chondrites, while the CI and CM material existed as cm to meter size objects. In their analysis, Goswami and Lal (1979) have considered the difference between the spallogenic and radionuclide exposure ages of these meteorites as a measure for pre-compaction irradiation durations. Such an approach is logical since the spallogenic exposure ages should integrate over both pre-compaction and recent space exposures, whereas, the radionuclide exposure ages reflect only the recent space exposure durations of the meteorites as small objects.

Literature data on spallogenic and radionuclide exposure ages and hence on values of T_{PC} are available only for three gas-rich CM chondrites: Murchison, Cold Bokkeveld, and Nogoya. We have therefore initiated radionuclide and noble gas measurements of several other gas-rich meteorites, with total exposure age < 10 m.y., to obtain additional information on T_{pc} for various types of gas-rich meteorites. The results of the present work is shown in Table-1. The spallogenic ages and the ^{26}Al exposure ages are from literature data. (Work is currently in progress to obtain noble gas exposure ages of aliquots taken from the same samples used for radionuclide measurements). It can be noted from Table-1 that the new data for the CI chondrite Orgueil and CM chondrite Murray further strengthen the earlier hypothesis of short pre-compaction irradiation durations for CI and CM meteorites. The lower spallogenic age for Murray, which is for the bulk sample, probably reflects gas-loss from the matrix material as is the case with Orgueil bulk samples.

Table-1: Noble gas and radionuclide exposure ages of gas-rich meteorites

Meteorite	Type	Exposure Age (m.y.)			
		^{21}Ne	^{38}Ar	^{26}Al	^{53}Mn*
Murchison	CM	$0.87;1;1.3^{+}$	-	1.6	2
Murray	CM	3.5	-	>2**	5.7
Orgueil	CI	$4.5;10.7^{+}$	$\geq 10^{+}$	>2**	>10**
Kapoeta (L)	Howardite	2	3^{+}	-	3
Kapoeta (D)		-		-	3

*Present work; Production rate of ^{53}Mn used = 414 dpm/kg(Fe+1Ni) +Data for mineral separates; the Kapoeta data are for mineral separates from basaltic clasts; **Values based on saturated activity. Source of Data : Bogard et al.(1971); Heymann and Anders (1967); Jeffery and Anders (1970); Kerridge et al.(1979); Macdougall and Phinney (1977); Mazor et al. (1970); Rajan et al. (1979); Rowe and Clark (1971); Signer and Suess (1963).

In addition to the data on CI and CM chondrites we also present the results of ^{53}Mn studies on samples of both dark and light phases of the gas-rich Kapoeta howardite. The radionuclide exposure age for this meteorite is almost identical to the noble gas exposure age, which again constrains the pre-compaction exposure duration of this meteorite to $< 10^{5}$ yrs. We would like to note here that the following indirect evidences further suggest that the T_{pc} values are probably very small ($\leq 10^{6}$ yr) for all gas-rich meteorites. First, the exposure age distributions for both gas-rich and non-gas-rich meteorites of different types are similar, thus excluding the possibility of long pre-compaction exposure durations in excess of a few m.y. for the gas-rich meteorites. Second, the only two documented cases involving differential cosmogenic exposures of xenoliths in gas-rich meteorites (Schultz et al. 1972; Schultz and Signer 1977) indicate shielded pre-compaction exposure durations of about a million years for some of the xenoliths. Although the possibility

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of loss of cosmogenic noble gases due to thermal diffusion and shock induced effects etc. may lead to an underestimation of the values of T_{PC}, such a possibility can be definitely ruled out in the case of noble gas data for grain separates from CI and CM chondrites. In the case of differentiated meteorites, the effective retention of solar wind noble gases and solar flare tracks also indicate an effective retention of cosmogenic noble gases as well.

The short pre-compaction irradiation durations for all types of gas-rich meteorites, inferred from both direct and indirect evidences noted above, pose a serious problem in understanding the observed irradiation features in these meteorites as regolithic features. In the case of CI and CM chondrites the model proposed by Goswami and Lal (1979) seems to be consistent with most of the observed irradiation features including the high percentage of gas-rich members. However, this model is not applicable in the case of differentiated gas-rich meteorites like the Kapoeta howardite. Some of the plausible hypotheses that need further attention for an adequate explanation of the irradiation features in different types of gas-rich meteorites are outlined below :

i) As pointed out by Goswami et al. (1976), it may be possible that the irradiated components in gas-rich meteorites have had a very different exposure history compared to the unirradiated counterparts. Collaborative experiments are planned to perform noble gas measurements on irradiated and non-irradiated grain separates to check this possibility.

ii) In the case of the differentiated gas-rich meteorites, if one follows the evolutionary scenario proposed by Scott and Rajan (1981), in which the differentiation processes took place in kilometer-sized objects prior to the formation of parent bodies, one can postulate that during the collisional aggregation of the differentiated objects to form the parent bodies, some of them may suffer catastrophic fragmentation producing a swarm of cm to meter sized objects which will receive solar flare, solar wind irradiation for a short time prior to their accumulation into the parent bodies. Such a scenario (Wetherill pers.comm.) is applicable to all types of gas-rich meteorites.

iii) If the gas-rich meteorites are present-day regolith breccias, and the irradiation features seen in them are imprinted in recent times, our approach for obtaining T_{PC} values is not correct. However, data available on compaction ages of gas-rich meteorites indicate that the pre-compaction irradiation most probably took place in ancient times (Macdougall and Kothari 1976). Further, in the case of several CM chondrites, whose cosmogenic exposure ages are less than a m.y., it is impossible to explain the observed irradiation features as regolithic features even with this assumption.

iv) To explain the high percentages of gas-rich chondrites and achondrites, Housen et al. (1979) suggested that the asteroids may have multi-layered regolith structures resulting from repeated collisional fragmentation and reaccumulation processes. Whether this in fact is possible from a dynamical view point is yet to be tested analytically. The constraint of short pre-compaction irradiation durations is however a major problem in any model involving regolith irradiation scenario.

In conclusion, we consider it important that the constraint on the pre-compaction exposure duration is explicitely considered in any attempt to understand the irradiation history of the gas-rich meteorites. It also seems necessary to consider separately the irradiation history of the differentiated and undifferentiated gas-rich meteorites. While regolith growth processes on meteorite parent bodies must have resulted in fragmentation, excavation and redistribution of material, and may also be responsible for some of the observed petrographic features in gas-rich meteorite breccias, they do not seem to contribute much towards the observed irradiation features in these meteorites.

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THE ORIGIN OF ACHONDRITE BRECCIAS, Roger H. Hewins, Dept. of Geological Sciences, Rutgers University, New Brunswick, N.J. 08903.

Introduction Much work on achondrite breccias has stressed similarities to breccias from the lunar surface, although some important differences have been noted (Housen et al., 1978; Hewins, 1979). In view of the recent publication of models for planetesimal accretion and asteroidal collisions (Housen et al., 1979; Hartman, 1979) plus comparative summaries of lunar and terrestrial breccias (James, 1977; Stoffler et al., 1979), achondrite breccias must be reconsidered. Specifically, the characteristics of the related howardite-eucrite-diogenite group which are almost certainly from a single parent body must be listed for comparison with diagnostic criteria for different breccia-forming processes as these become defined.

Achondrites and Other Breccias With a large single terrestrial impact, monomict breccias, polymict breccias and polymict breccias with abundant melted material (suevite), as well as impact melt sheets, are produced. These represent basement material, ejecta, and ejecta overtaken by impact melt, and comparable rocks from the moon include cataclastic anorthosite light matrix breccia and poikilitic melt rock (James, 1977; Stoffler et al., 1979). An additional type found on the lunar surface as a result of extended exposure to small impacts is soil breccia, which is characterized by very high abundance of glassy particles, particularly agglutinate, high concentration of projectile remnants, high track densities and high gas concentrations.

Diogenites and cumulate eucrites are dominantly monomict or unbrecciated and can be interpreted as representative of basement material beneath large craters. Ferroan (monomict?) basaltic eucrites may be similar or could represent ejecta from small impacts on surface flows formed very early before the development of an extensive regolith. An early formation and subsequent burial might explain their metamorphism (Harlow and Klimentidis, 1980; Harlow and Delaney, 1981).

Contaminated diogenite and cumulate eucrite which contain small proportions of Mg-rich basalt (Garcia and Prinz, 1978; Hewins, 1981) may represent interfaces between the monomict breccias and other breccias. Polymict eucrites can be interpreted as breccias transitional to those formed by larger scale impacts, the howardites. (Alternative models for simple achondrites are considered below).

Properties of howardites relavent to their impact origin are listed in Table 1. Petrographically, lunar light matrix breccias and glass-poor feldspathic and light grey breccias (James, 1977; Stoffler et al., 1979) resemble howardites. Glass and impact melt rocks are difficult to find in all howardites except Malvern, Bununu and Kapoeta, which have therefore received perhaps disproportionate attention (Brownlee and Rajan, 1973; Rajan et al., 1974; Noonan, 1974; Simpson, 1975; Desnoyers and Jerome, 1977; Rajan et al., 1975; Dymek et al., 1976; Kirsten and Horn, 1977; Hewins and Klein, 1978; Klein and Hewins, 1979). It has been emphasized (Housen et al., 1978) that even these exceptional breccias have much less glass than lunar soil breccias. The majority of howardites therefore represent low shock intensity (unmelted) ejecta from sizeable craters.

A major question, whether any howardites represent gardened regolith, remains. There have been reports of agglutinate-like material in some howardites (Rajan et al., 1974) but others (e.g., Hewins, 1979) have not observed true agglutinates in howardites. Lunar agglutinates - porous, cindery, glass-welded aggregates - indicate repeated micro-meteorite impacts. Howardite melt particles are dominantly fine-grained clast-laden melt rock containing residual glass. In one case (Labotka and Papike, 1980) these particles were described as "fused soil", an unfortunate usage since this has genetic implications. Several studies (Rajan et al., 1975; Kirsten and Horn, 1977; Klein and Hewins, 1979) have suggested that all these particles may have originated in a single event, making these howardites suevite-like deposits. The best case for a suevite-like howardite can be made for Bununu, where large bodies of melt rock have smooth boundaries - the so-called "intrusive" melt (Bunch, 1975; Klein and Hewins, 1979). Elsewhere melt rocks occur as clasts presumably not co-genetic with the breccia, consistent with reworking of very immature soil. Housen et al. (1979) developed a model for regolith evolution on asteroidal bodies which showed that ejecta blanketing would produce glass-poor rocks like howardites rather than lunar soil.

At least three howardites are gas-rich (Table 1) and there is evidence that Malvern has been depleted of rare gases (Kirsten and Horn, 1977). This indicates surface exposed material but, rather than represent true soil breccias themselves, these howardites may contain such a component stirred in during deposition. These howardites belong to a Ni-rich group (Hewins, 1979) which contains carbonaceous chondrite clasts or melt associated with Ni-rich metal or both (Table 1). The two clast types indicate projectiles with different velocities at different times. The breccias were probably lithified at 3.6-4.2 b.y. (Rajan et al., 1975; Dymek et al., 1976; Kirsten and Horn, 1977; Klein and Hewins, 1979), the time of glass formation, and carbonaceous clasts might possibly have been acquired earlier along with gas and stirred in as part of the dark fraction.

Achondrites and Asteroid Models Housen et al. (1979) have shown that cratered asteroidal bodies should have blanketing rates greater than excavation rates, which satisfactorily explains the low glass content and relatively low gas content of howardites relative to lunar soils. However, this is a model for projectiles colliding with full fledged asteroidal bodies. The accretion of planetesimals and the assembly of such bodies into an asteroid could produce breccias which, depending on the time of melting, could be achondritic. The only meteorites which are bedded are the CV group (Martin et al., 1975; King and King, 1978) and since these contain CAI they could be described as cosmic sediments. However these also contain CM(?) clasts, which implies prior accretion, warming and redistribution of water (McSween, 1979) presumably in another body.

Recently relatively tiny differentiated planetesimals have been proposed (Wood, 1978, 1979; Scott, 1979; Wilkening, 1979) to explain the number of groups, the structures and the thermal histories of some fractionated meteorites. Presumably, if extinct radionuclides such as ^{26}Al are important in heating such material, these might be early accreted planetesimals. Scott (1979) has argued that iron and silicate fractions seldom mixed when such planetesimals were assembled into larger bodies. However mixing of the crusts of such planetesimals could conceivably produce achondrite breccias. One polymict eucrite is particularly fascinating in this regard, since it contains one clast with different oxygen isotopes which must have originated from a different reservoir than the other clasts (Grossman et al., 1981). Additional isotope studies might lend support to this idea of assembly of differentiated planetesimals. If so, this would dispose of the problem of finding simple models for the fractionation of cumulate eucrites (Ma and Schmitt, 1979; Mittlefehldt and Drake, 1980). In addition, some monomict achondrite breccias could possibly have formed during accretion of planetesimals.

Hartmann (1979) has modeled the assembly or interaction of similar sized planetesimals or asteroids. In the case of massive bodies, collision leads to fragmentation but if velocities are low enough the debris is reassembled by gravity. This is another process which might produce achondrite breccias or megabreccias, but it is not clear how to recognize such breccias.

Mesosiderites are perhaps the most perplexing polymict breccias. The intimate mixture of metal and silicate, the very fine-grained silicate matrix in Type I mesosiderites, the shard-like nature of some clasts, particularly of olivine, and the occurrence of clast-laden impact melt rocks (Type IV mesosiderites) all point to some form of impact process to generate mesosiderites. However the thermal history (e.g. Kulpecz and Hewins, 1978) requires extremely deep burial after the impact event. This is not consistent with normal cratering but would occur naturally in the early stages of accretion. It is therefore suggested that mesosiderites represent a differentiated planetesimal, as discussed above and comparable to Scott's 1979 suggestion for the IIE group. Since accretionary velocities are low, the intimate mixture in the breccia suggests that the planetesimal was still hot and partially molten when it was accreted.

Future Work (1) Howardites appear to be ejecta deposits, not soils, formed very late on asteroid surfaces. Some simpler achondrite breccias could be formed by planetesimal accretionary processes and diagnostic criteria for these need to be defined.

(2) Siderophile element analyses of melt rocks, metal and carbonaceous chondrite clasts would indicate if there was more than one projectile type in Ni-rich howardites.

(3) Radiometric dating of different glasses from one Ni-rich howardite would indicate if there was a single time of impact.

(4) Dating of shocked igneous clasts in Ni-poor howardites might show whether these breccias were assembled early or as late as Ni-rich howardites.

(5) SEM and microprobe studies of howardite matrix will indicate the extent and variability of recrystallization and metamorphism.

(6) Oxygen isotope studies of eucrites and howardites might provide additional evidence for heterogeneous parent bodies which might be explained by planetesimal accretionary processes.

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Table 1

	Dark Light	Rare Gas	Ni ppm	Ni Metal	Melt, Glass	Carb. Chond.	Age b.y.	Other
Malvern		±(19)	372(4)	✓	✓		3.6(6)	clastic
Bununu		±(29)	420(4)	✓	✓		4.2(29)	
	D	+						
Kapoeta		(24)	374(4)	✓	✓	✓(34)	3.6 (19,29)	tracks
	L	−						
Bholgati			584(4)	δ	δ	✓(14)		
	D	+	670					
Jodzie		(24)	(24)			✓(2)		
	L	−	54					
Petersburg			~2000(12)	±				meta(12)
Washougal			125(7)			✓(3)		
Frankfurt					δ(22)			
Yurtuk			75(7)		δ(22)			meta(22)
Pavlovka			77(7)		δ(22)			
Zmenj			38(7)					
Massing			61(7)					
Le Teilleul			88(4)97(7)					

Sources of data are indicated by numbers in parentheses. These refer to position in list of references.

MODELING THE EVOLUTION OF ASTEROIDAL REGOLITHS, K. R. Housen, Shock Physics and Applied Math, M/S 45-43, Boeing Aerospace, Seattle, WA, 98124

A number of lines of evidence suggest that many meteorites originated on asteroids (Anders, 1964, 1975; Chapman, 1976; Wasson and Wetherill, 1979; Wood, 1964, 1969). Furthermore, the brecciated and gas-rich meteorites appear to have formed in regoliths because they exhibit many characteristic features of breccias sampled from the lunar regolith, e.g., charged-particle tracks, solar wind implanted gases, agglutinates, etc. (Wilkening, 1971, 1973; Brownlee and Rajan, 1973; Macdougall, et al., 1974; Poupeau et al., 1974; Rajan, 1974; Price et al., 1975). Thus the study of asteroidal regolith evolution is an important element in the study of the origins of meteorites.

When discussing asteroidal regoliths it is convenient to distinguish between two epochs of their evolution: the evolution during the phase of asteroidal accretion and the subsequent "modern-day" evolution. During accretion material which impacted proto-asteroid surfaces was fractured and comminuted, although not extensively because the impact velocities had to be low enough to result in net accumulation. Asteroidal embryos grew by building up layers of broken, weakly bonded rocky debris, i.e. layers of regolith. The regolith in some asteroids may have since been destroyed through the action of heating events or, in large bodies, through the action of high internal lithostatic pressures. Still, many bodies should have survived as being composed mostly of regolith. Such massive collections of debris are referred to here as "accretional megaregoliths".

The buildup of regolith through accretion ended when the relative velocities of asteroids were increased to the presently observed value (about 5 km/s). During these high velocity impacts part of the crater ejecta are launched to beyond escape velocity. In fact, most asteroids are presently experiencing net erosion rather than accretion. Even so, if an asteroid is large enough to retain a non-negligible fraction of its debris, then the continual bombardment of its surface results in the formation of a regolith layer. Of course for those bodies which accreted and retained a primordial regolith-like surface by escaping thermal metamorphism, the bombardment merely serves to comminute the extant regolith. For bodies composed of consolidated materials, regolith is created when large craters penetrate the existing debris layer and excavate "pristine" substrate.

The evolution of a regolith ends if an energetic collision occurs which fragments and disperses the asteroid. This may occur rather quickly for a small body. On the other hand, a large asteroid may repeatedly experience collisional events which are sufficiently energetic to cause major internal fracturing but not dispersal of the fragments against their mutual gravitational field. During such events surficial layers of regolith may be mixed into the asteroid's interior. Thus, prior to dispersal, large bodies should evolve into gravitationally-bound balls of regolith, which Housen et al. (1979a) have referred to as asteroidal "megaregoliths" (in contrast to the accretional megaregoliths discussed above).

An important question in the study of meteorites is whether they originated in accretional megaregoliths (if so they might contain information regarding the ancient solar wind and the collisional environment in the asteroid belt) or whether they formed more recently. Some have favored an accretional origin in order to explain the brecciation textures and irradiation features observed in gas-rich meteorites (Lal and Rajan, 1969; Pellas et al., 1969; Wasson, 1972) and the total quantity of brecciated material observed among all classes of meteorites (Chapman, 1976). Conversely, Anders (1975, 1978) has argued for an origin in more recent times. In principle, the question of an early versus a recent origin might be answered by constructing detailed models which describe regolith evolution and the properties of regolith-derived meteorites for each of the two epochs discussed above. However, because of a lack of knowledge regarding the early solar system environment most models have only examined the plausibility of a recent origin.

Several models of regolith growth have been constructed. These models have been reviewed and compared elsewhere (Housen et al., 1979b; Housen, 1981a; Housen and Wilkening, 1981) so they will only be highlighted here. Chapman (1971; updated, 1976) made the first attempt at determining whether or not asteroids might develop regoliths. He considered the degree to which large-crater ejecta blankets were eroded by small-scale impacts in the time intervals between large blanketing events. He concluded that asteroids larger than a few hundred kilometers in diameter should possess "large-scale" regoliths whereas smaller bodies should have rocky, though possibly dusty, surfaces. Housen (1976) assessed the actual depth of regolith by computing the average distance below an asteroid's surface to the undisturbed substrate. The regolith depth on a 200 km diameter asteroid was found to be roughly 100m. Housen et al. (1979a;b) noted that the population of impacting projectiles in the asteroid belt is currently such that small craters collectively occupy more surface area than do large ones but that the few large craters excavate more volume than do the small ones. Consequently, they tried to find an "improved" estimate of regolith depth by considering only the parts of an asteroid's surface which were saturated by small impacts. The areas occupied by large craters were avoided because these areas were thought to be unrepresentative of most of the surface; their inclusion would result in an unrealistic average regolith depth. The crater-saturated portion of the surface was referred to as the "typical region". While the larger craters themselves were excluded from the typical region, their widely dispersed ejecta deposits were included. Regolith growth was dominated by deposition of material from craters outside the typical region because, as mentioned above, large craters excavate more volume than do the small impacts. Rocky asteroids in the diameter range 100-1000 km were found to generate kilometer-thick regoliths which were very poorly gardened due to the rapid buildup of debris in the typical region. Material deposited on the surface was quickly shielded from low energy radiation thus explaining the immaturity of gas-rich meteorites compared to lunar breccias. Housen et al. found that the radiation exposure ages of regolith material agreed with those observed in gas-rich meteorites and furthermore suggested that the prevalence of brecciated meteorities could be explained by the collisionally generated megaregoliths developed prior to asteroid dispersal. These calculations supported the idea that many gas-rich meteorites originated in modern-day regoliths. Duraud et al. (1979) briefly described a model for the equilibrium depth of regolith on small bodies. The erosive and depositional effects of cratering on an existing regolith layer were considered. For asteroids 20 km and 200 km in diameter, equilibrium depths of 2 m and 200 m were computed. Langevin and Maurette (1980) have also constructed a model in order to isolate the critical parameters in determining regolith depth. Their work is similar to that of Housen et al. in the sense that only a typical region was considered. However, the two models differ in their definitions of crater saturation and in their adopted values of input parameters (Housen, 1981a). The most important difference lies in the assumed distribution of crater ejecta velocities. Langevin and Maurette effectively assumed ejecta to be less widespread than Housen et al. and as a result found the regolith depth to be a factor of 2-3 less than the Housen et al. estimates.

At present, our attempts to model regolith evolution are hampered by poorly known input parameters. Moreover, while we can test the sensitivity of our models to uncertain parameters, in many cases it is difficult to estimate the magnitude of the uncertainties. For example, regolith models require knowledge of the crater size frequency distribution. Because we have no direct observations of asteroid surfaces we must arrive at the crater distribution indirectly. Housen et al. (1979a) estimated the distribution by employing estimates of the mass frequency distribution of projectiles and relationships between impact energy and resulting crater size. Langevin and Maurette (1980) have used an alternate method which derives the asteroidal crater distribution from the observed lunar crater population, assuming that the shape of the projectile distribution at 3 AU is the same as that at 1 AU. Both of these methods are subject to uncertainties, the size of which are difficult to determine. In this regard we should note that regolith depth calculations are rather sensitive to the shape of the crater distribution. For example, Housen et al. (1979a) approximated the number of craters of diameter D or larger as being proportional to D^a. They found that a 15% change in $\underline{a}$ produced roughly a factor of 3 change in regolith depth. Another sensitive parameter is the velocity distribution of crater ejecta, which determines the amount of nonescaping debris and the extent to which large craters can deposit material into the typical region. Langevin and Maurette (1980) have found order of magnitude variations in the computed depth depending on the assumed dependence of ejecta velocity on crater size.

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In addition to these uncertainties, Housen (1981b;c) has shown that our estimates of regolith depth are subject to statistical uncertainties which arise because of the stochastic nature of regolith evolution. For example, even if we could exactly specify the crater size frequency distribution, we could not predict, with absolute certainty, the number of craters which form on the surface of any given asteroid. In this light the computed average regolith depth can be viewed as a random variable. The coefficient of variation (i.e., the standard deviation divided by the mean) of this random variable can be shown to be about 70%. Futhermore, if we wish to compute the regolith depth at any point on a asteroid's surface then an additional uncertainty arises because of the variation in depth over the surface. In this case the coefficient of variation is roughly unity. Note, these uncertainties cannot be reduced until we have photographs of asteroidal surfaces so that the crater distribution can be determined exactly. Thus, for the present we cannot expect to compute regolith depth to within perhaps a factor of a few.

While these modeling efforts have increased our understanding of regolith evolution, much work still needs to be done both in the area of improving estimates of input parameters and in extending our models into uncharted areas.

(1) The velocity distribution of crater ejecta determines the amount of escaping debris and the areal dispersion of nonescaping ejecta. This is important both in computing regolith depth and in simulating the charged-particle irradiation history of a regolith. Currently our estimates of ejecta velocities are based on only a few low energy impact events which were conducted in only two target materials and at essentially one impact energy and gravitational acceleration. How does the velocity distribution change when we consider different target media or the much higher impact energies (and momenta) and lower gravitational fields appropriate to the asteroidal cratering environment? Also, what is the effect of impacting into a layered medium, i.e., a coherent substrate overlain by a layer of uncohesive regolith? Clearly we need more experimentation in this area, but only if accompanied by a theoretical understanding of how ejecta velocites should scale with impact energy, momentum, gravitational acceleration, etc.

(2) The "lifetime" of a surficial regolith layer depends on the collisional fragmentation lifetime of an asteroid, which in turn depends on the impact energy required for fragmentation. Presently, our estimates of the fragmentation energy are based on extrapolations of small-scale laboratory data over some 15-20 orders of magnitude in energy. The uncertainties involved are themselves uncertain. Can numerical computer codes shed any light on the problem of asteroidal fragmentation?

(3) Our present estimates of the projectile population in the asteroid belt suggest that most meteorites should be derived from the more energetic, and even destructive collisions. How is material liberated from asteroids in major impact events? Perhaps these events lend to strip away the uncohesive regolith layers. If so, then regoliths may not need to be as deep as previously thought in order to produce the observed abundance of brecciated meteorites. At any rate, we cannot determine the extent to which asteroids develop megaregoliths without a better understanding of these events. Again, numerical codes might be applied to this problem.

(4) Seismic waves have been suggested as playing an important role in regolith evolution, both in lofting (and therefore mixing) surface material and in creating large volumes of debris through spallation at the antipode of the impact point (Cintala et al., 1979; Langevin and Maurette, 1981; Horz and Schaal, 1981). Quantitative calculations need to be performed in order to assess the magnitude of any seismic effects.

Regolith modeling has come a long way in the past decade. We can be reasonably confident that the larger asteroids are covered by debris layers which are hundreds of meters to several kilometers deep. These regoliths are expected to be very immature by lunar standards. Quantitative predictions have lent support to the idea that brecciated and gas-rich meteorites originated in modern-day asteroidal regoliths. Further experimentation and modeling can only increase our understanding of the evolution of asteroid surfaces and the origins of meteorites.

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VOLATILE TRACE METAL TRANSPORT IN PLANETARY REGOLITHS. R.M. Housley and E.H. Cirlin, Rockwell International Science Center, Thousand Oaks, CA. 91360

In nebular condensation schemes, which have been discussed in the literature, a number of volatile trace elements are predicted to condense after condensation of the major oxide, metal, and silicate phases is essentially complete. It is plausible therefore that they might initially reside primarily on the surface of grains of these previously condensed phases.

In igneous processes many of these same volatile elements are incompatable with the major crystallizing phases and are not incorporated in them. They then remain mobile until considerable porosity develops. They may finally come to reside largely on microcrack, vesicle, and vug surfaces.

During low pressure metamorphic processes these surface volatiles can move at temperatures low enough that melting or appreciable sintering of the major phases does not take place. Thus during both igneous and thermal or impact induced metamorphic processes volatiles are expected to become enriched in low grade breccias and unconsolidated fines and depleted in melt rocks and high grade breccias.

A considerable amount of data supports the importance of transport processes in determining the trace element content of lunar regolith and breccias. The most significant results of reported work on Zn, Cd, and Pb including our own thermal release studies (Cirlin and Housley, 1979; 1980; 1981) may be summarized as follows: 1. Most of the Zn, Cd, and initial Pb in lunar regolith samples are on the surfaces of grains. 2. The contents of Zn, Cd, and initial Pb in lunar regolith samples are considerably higher than those in typical parent rocks. 3. Normalized to chondritic values Cd is enriched in the regolith more than twice as much as Zn.

In order to interpret these results and define experiments to advance our understanding of volatile transport processes we have developed a tentative model to predict the vapor pressures of Zn, Cd, and Pb as a function of temperature in lunar and meteoritic samples. We assume that both Fe and FeS are present so that the S activity is determined by the reaction

$$2Fe + S_2 \rightarrow 2FeS \quad .$$

In this case published thermodynamic data (Robie and Waldbaum, 1968) imply that Zn and Cd are present as sulfides, and Pb as metal. We then assume that the solid solubilities of Pb in Fe and ZnS and CdS in FeS are very small so they are present at near unit activity. The results are shown in Figure 1.

It seems inescapable that considerable volatile transport must have occurred during the metamorphism of meteorities. This work was supported by Contract No. NAS9-11539.

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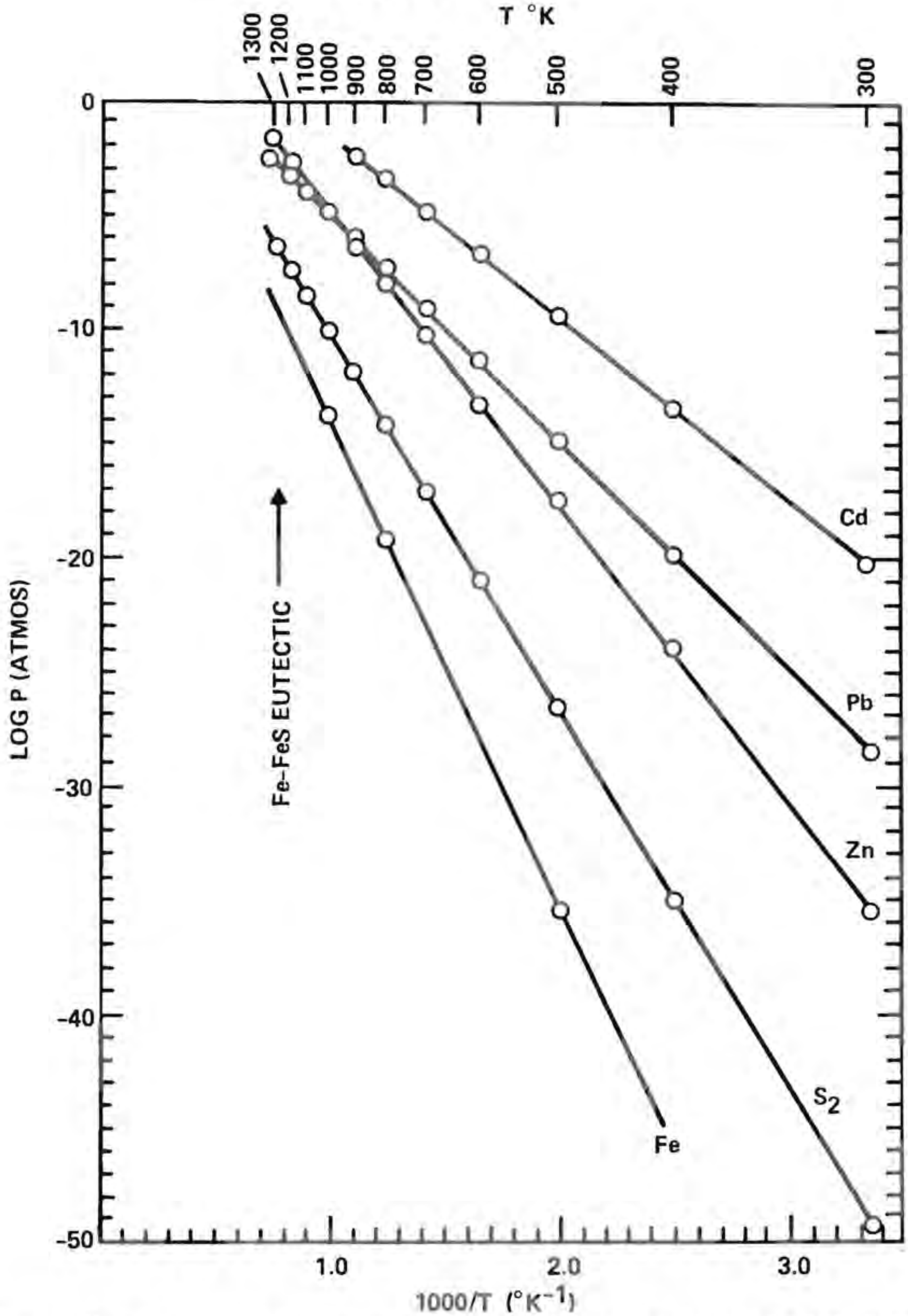

Fig. 1. Vapor pressures of several interesting elements calculated for lunar and meteoritic conditions on the basis of model described in text. Significant volatile transport is expected for pressures about about 10^{-10} atmos. Thus Zn, Cd, and Pb may readily move through unconsolidated regolith.

AN EXTENSION OF LUNAR RUST PETROGENESIS TO THE VOLATILE ELEMENT REGIME OF LIGHT-DARK CHONDRITIC METEORITIES

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Native FeNi (e.g., kamacite, taenite) is ubiquitous to lunar rocks and meteorites. It is unstable, however, in the presence of halogens, even at very low fugacities; in the presence of chlorine, it reacts to form $FeCl_2$, lawrencite, which, although highly deliquescent, is stable in the anhydrous lunar environment. Exposure to terrestrial water vapor has resulted in oxydration of this lawrencite to form akaganéite (FeO(OH,Cl)), "lunar rust" (Taylor et al., 1974). Hence, the presence of Cl-bearing rust (containing 1-6 wt% Cl) in lunar rocks, and probably meteorites, indicates that Chlorine has been mobile during the petrogenesis of these rocks.

In lunar rocks, the chemistry and textural associations of akaganéite, native FeNi, and other volatile-bearing phases and the bulk-rock distribution of volatile elements is particularly instructive with regard to the nature and timing of volatile element mobility and emplacement; furthermore, these data provide an insight into the origins of these volatile elements (e.g., Hunter and Taylor, 1981a).

The association of rust, sphalerite, and troilite with FeNi metal is commonplace in Apollo 16 highland breccias and impact generated melt-rocks. We have been able to construct a sequence of events that may have led to this paragenesis. Zinc chloride, $ZnCl_2^o$, has a significantly higher vapor-pressure than Zn^o, ZnS^o, or ZnO^o, consequently, in the presence of chlorine, Zn (and Cd, Bi, etc.) readily transports in the vapor as the metal - halogen complex molecule. When this vapor comes into contact with native FeNi, reaction occurs with formation of lawrencite periferal to the metal particles; the zinc is thereby released. This zinc reacts with troilite to form sphalerite, (Fe, Zn)S. The overall reaction may be written;

$$(ZnCl_2)_v + Fe + FeS \rightleftharpoons FeCl_2 + (Fe, Zn)S.$$

Of course, the proportions of Fe and FeS are far in excess of the $ZnCl_2$. The textural associations are particularly significant with respect to this line of reasoning. The lawrencite (now akaganéite) and sphalerite typically occur as marginal placements or encrustations surrounding the native FeNi and troilite. If no troilite were present, the Zn may have deposited along cracks and grain-boundaries. The Pb, Zn, Cl sulphates and phosphates reported from 66095 (El Goresy et al., 1974) may have formed by similar mechanisms. Liberation of HCl during the oxyhydration of lawrenceite may further complicate the situation, with remobilization and redeposition of acid-soluble salts along cracks and grain-boundaries.

Inherent to these depositional models, is that the volatile-bearing vapor was mobile as a late-stage component subsequent to the formation of the native FeNi and troilite. There is circumstantial evidence to support this contention. Wänke et al. (1981) and Ebihara et al. (1981) have measured constant volatile inter-element relationships from a diverse suite of petrologic types preserved in clast-laden impact-melt breccia, 66095 ("Rusty Rock"), the most volatile-rich sample returned from the Apollo missions. For example, absolute abundances of Zn and Cl vary by over an order of magnitude, but a near-chondritic ratio is present in all the samples analyzed. In addition, correlations with Cl exist for Br, Cd, In, Te, Ga, and As. Less detailed studies on other breccias (e.g., 61016 - Krähenbühl et al., 1973) have shown similar relationships. The implication is that all these volatile elements were deposited from a vapor phase subsequent to the formation of these breccias (Hunter and Taylor, 1981a).

The variable abundances of volatile elements within different lithologies represented by the highland breccias and melt-rocks, even within the same breccia specimen, is a result of two factors (Hunter and Taylor, 1981b); firstly, the availability of native FeNi as a getter or sink for these elements, and secondly, the relative porosities of the constituent lithologies, a problem of "plumbing". Melt rocks contain an abundance of metal, and cataclastic and brecciated rocks contain more voids and avenues for volatile-element penetration. As a consequence, rust is most abundant in these lithologies and may be absent from coherent ANT suite clasts and rocks (Hunter and Taylor, 1981b).

The majority of Apollo 16 rocks contain akaganéite and/or schreibersite, $(Fe, Ni)_3P$ (Hunter and Taylor, 1981b). The former is evidence of halogen mobility and the latter of phosphorous mobility. These significant observations raise the question as to the origin of these volatile elements in the lunar highlands. Krähenbühl et al. (1973) suggest fumarolic enrichment. The ubiquitous presence of a "hidden" KREEP component in highland rocks prompted Garrison and Taylor (1980) to suggest remobilization of KREEPy volatiles during impact metamorphism, a model supported by the thermal release experiments conducted by Cirlin and Housley (1980). The Cl and P in KREEP is present as phosphate, apatite or whitlockite. Impact-generated melts on the moon contain a significant component of solar wind emplanted elements (e.g., C and H) derived from incorporated regolith. These impart a dominant reducing environment onto the intrinsic fO_2 conditions of the melt and producing an autoreduction. Incorporation of this KREEP component into the low fO_2, impact-generated melts, in which phosphide is stable relative to phosphate (Friel and Goldstein, 1977), effects a de-coupling of Cl and P; this may result in formation of a late-stage Cl-rich vapor phase (presumably enriched in other incompatible volatiles) in the ejecta blanket (Hunter and Taylor, 1981a).

Differences in various volatile abundances between the light and dark portions of certain brecciated chondrites are apparent (e.g., Dreibus and Wänke, 1980). Indeed, examination of some of these meteorites, including recent falls, has revealed the presence of considerable rust in both the light and dark portions. The amount is significant, particularly for finds. It is instructive to attempt a synthesis of the origin and deposition of these volatiles in meteorites, within the context of our knowledge of the lunar situation. Some of the rust observed in these meteorites is Cl-bearing and, by analogy with lunar rocks, has formed by similar reactions involving Cl vapor and native FeNi producing lawrencite with subsequent oxyhydration.

Sampling of the moon has been somewhat inadequate, but it is far superior to our sampling of the various meteorite parent bodies. Analogies may be made between several lunar highland rock types and meteorite lithologies (e.g., Taylor, 1982, this volume). However, there is a paucity of impact melt-rocks in the meteorite sample, with the possible exception of the mesosiderites, and there is no analogy to KREEP. Models for the origin of volatile enrichment in some lunar rocks may have limitations, but those for meteorites can be little more than speculation.

It has been suggested (e.g., Wilkening, 1976) that the dark fraction volatile enrichment in chondrites is derived from an admixed volatile carbonaceous chondrite component. McSween and Lipschutz (1980), however, suggest that there is no compelling petrographic evidence for this component in the unequilibrated portions of the H-group chondritic breccias. They propose a genomict origin, with the dark portion representing accretional hybrid mixtures of un-equilibrated H-chondrite and pulverized equilibrated H-chondrite similar to the light clasts. By analogy with lunar breccias, we may expect extensive volatile remobilization and deposition during impact metamorphic processes on meteorite parent bodies. There is also evidence for volatile mobility during planetary regolith formation (e.g., Housley and Cirlin, 1982, this volume). The fractionation of volatiles between dark and light portions is attributed by Dreibus and Wänke (1980) to a two stage process: First, remobilization of volatiles from the interior to the surface of the chondrite parent body in response to accretional metamorphism of its interior; and second, mixing of the volatile rich (= dark) portions with deeper volatile-poor, light fractions excavated during subsequent impact processes and regolith formation.

The presence of rust in these chondrites indicates that chlorine, at least, has been mobile. Other volatile elements, e.g., Br, I, In, Tl, Bi, Cd, and Cs, similarly are enriched in these chondrites and show a broadly similar fractionation between dark and light portions, albeit with variable inter-element ratios (Reed and Allen, 1966; Rieder and Wänke, 1969; Bart and Lipshutz, 1970; Dreibus and Wänke, 1980).

The contention that porosity is a major factor in determining the redistribution of volatile elements during lunar impact metamorphism may be a factor in consideration of the apparent fractionation observed in these chondrites. The dark matrix portions are unequilibrated (e.g., McSween and Lipshutz, 1980; McSween et al., 1981) and contain abundant chondrules, lithic fragments, and angular mineral grains in a fine-grained matrix. The light portions are generally granoblastic and more recrystallized. It is likely that the dark fraction has a higher porosity than the light and, therefore, a greater permeability to a fugitive volatile-bearing vapor phase.

The mode of deposition of volatiles in meteorites may be very similar to that in lunar rocks. However, the variable inter-element abundances imply either a different mode of transport or, more likely, a different source. We have questioned the basis for a lunar pristine volatile element chemistry (Hunter and Taylor, 1981b) on the grounds of the abundance of rust (and schreibersite) in lunar highland rocks; this rust clearly points to volatile element mobility subsequent to breccia formation. The microscopic distribution of the elements in the breccia may be a very ad hoc process. The observation that meteorites, including observed falls, may contain abundant Cl-bearing rust points to a similar elemental mobility during some chondrite petrogenesis. Furthermore, the HCl produced during oxyhydration of the "indigenous" lawrencite may further mobilize and re-distribute acid soluble elements, if only on a microscopic scale. The post-lithification, fugitive nature of many volatile elements suggests that a cautious approach should be employed when discussing the possible wider implications of volatile element abundances in meteorites.

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COMPOSITION AND ORIGIN OF CHONDRITIC BRECCIAS. Klaus Keil, Department of Geology, Institute of Meteoritics, University of New Mexico, Albuquerque, NM 87131, USA

INTRODUCTION. A breccia is a clastic rock composed of angular, broken rock fragments that are embedded into a finer-grained matrix [60]. Meteoritic breccias were first noted in 1843 [116], are widespread among different meteorite types (Table 1) and have for years been the objects of intensive research. Most formed by impacts on small asteroids, although accretionary breccias may also occur. Meteorites have also been subjected to shock events that did not result in brecciation. For example, localized melt pockets formed [29], fracturing of mineral grains and solid state conversion of plagioclase to maskelynite [9,107] took place. However, these rocks are not generally considered breccias and are therefore not treated here.

Previous breccia nomenclature has been complicated. The term monomict breccias has been used for rocks consisting of fragments and matrix of identical composition and origin; polymict breccias contain some foreign rock fragments of different composition and origin [150]. However, many fragments once thought to be foreign [150] were derived from host material by shock modification (e.g. crushing, melting, fractionation) [39-43, 45, 47, 48, 73, 74, 77, 159]. Genomict chondrite breccias contain fragments and matrix of the same compositional group but of different petrologic grade [152]. Rock fragments have been referred to as lithic fragments, lithic clasts, lithic inclusions, exotic inclusions, xenoliths, etc. Xenoliths are inclusions in a rock to which they are not genetically related [60]. I prefer this definition to that of Binns [10] who referred to any lithic clast, independent of its foreign or host-related origin, as a xenolith. I will use the term cognate clasts for those that are related to the host.

I discuss chondritic regolith, fragmental, impact melt, granulitic and primitive breccias and use nomenclature analogous to that applied to lunar rocks [143]. Lithic fragments (but not mineral xenoliths) [7] within breccias are described and are divided into xenolithic and cognate types.

WHY STUDY CHONDRITIC BRECCIAS? Recent increased interest in chondritic breccias is due to the following reasons: 1. Breccias shed light on the nature of regolith processes and impact and cratering mechanics on the relatively small (tens to hundreds of km radius) parent bodies, the thicknesses of regoliths, depths of excavation and burial, abundance of crushed, melted and fractionated material, and heat sources that metamorphosed chondrites prior to and after breccia agglomeration. 2. Dating of impact melt rock clasts in breccias places limits on the evolution through time of parent bodies and their regoliths. 3. Solar wind implanted gases and irradiation tracks place boundaries on the nature of lithification processes of breccias and histories of their constituents prior to and after agglomeration and consolidation. 4. Study of thermal histories of breccia constituents allows recognition of breccias formed by disruption and reassembly of parent bodies. 5. Abundance of different rock types in breccias suggests whether different meteorite classes come from a multitude of separate, compositionally homogeneous parent planetesimals or coexisted on one or a few parent objects. Also, these data provide clues to the stratigraphy (i.e. vertical and horizontal homogeneity) of parent objects in terms of chemical-mineralogic and metamorphic variabilities. 6. Clasts in breccias allow us to recognize new rock types not represented in meteorite collections as individual stones. Further, distinction may be made between xenoliths (e.g. residues of impacting projectiles) and seemingly exotic clasts that formed from host material by impact crushing, melting and

Table 1: Meteorites and meteoritic breccias.

STONES ACHONDRITES	Class	Breccia abundance	Examples	Selected references
Ca-poor	Enstatite (Aubrites)	Abundant[*]	Norton County[x], Cumberland Falls[+]	11, 114, 154
	Bronzite (Diogenites)	Nearly all	Johnstown[x], Aioun El Atrous[+]	38, 95, 98
	Olivine (Chassignites)	None		
	Olivine-pigeonite (Ureilites)	Rare	North Haig[+]	5
Ca-rich	Fassaite (Augite)	None		
	Augite-olivine (Nakhlites)	None		
	Polymict orthopyroxene-pigeonite-plagioclase (Howardites)	All[*]	Bununu[+], Kapoeta[+]	18, 30, 49, 58, 90
	Pigeonite-plagioclase (Eucrites)	Abundant	Pasamonte[x], ALHA76005[+](=77302)	108, 146
CHONDRITES	Enstatite	Rare	Abee[x]	27, 123
	H-group (Bronzite)	Common[*]	Plainview[+], Tysnes Island[+]	41, 74
	L-group (Hypersthene)	Common[*]	Mafra[x], Mezo-Madaras[+]	61, 148
	LL-group (Amphoterites)	Nearly all[*]	Kelly[x], Bhola[+]	19, 43
	HL-group (CV3, CO3)	Rare[*]	Leoville[+]	75,
	Carbonaceous II (C2)	Rare[*]	Murchison[+]	57
	Carbonaceous I (C1)	None[*]		
STONY IRONS	Pallasites	Common	Admire[x]	132
	Mesosiderites	Common	Hainholz[+], Mt. Padbury[+]	36, 37
IRONS	Octahedrites[xx]	All IAB, SOME IIE	Landes[+], Campo del Cielo[+], Netchaevo[+]	6, 20, 21, 163
	Hexahedrites	None		
	Ataxites	None		

[*] some containing solar wind gases

[x] Monomict, + Polymict

[xx] Brecciated octahedrites [66] are not breccias

fractionation. 7. Breccia studies provide a basis for comparison to lunar rocks. Although this comparison may provide for a better understanding of the processes that formed meteoritic breccias [118], one must be aware of significant differences between meteorite parent bodies and the moon that complicate comparison. Meteorites have not been studied in the field and, thus, genetic relationships between different types can only be inferred from laboratory studies. Meteoritic breccias may come from many parent bodies of diverse histories (some melted, some did not) that are different in composition from the moon (ultramafic vs. basaltic-feldspathic) and are much smaller; hence, cratering mechanics, relative impact velocities, and nature and quantity of impact products (melt rocks, agglutinates, glass spherules) are different. Finally, meteorites must survive atmospheric entry and, thus, only relatively tough regolith breccias are known; "soil"-type regolith samples akin to lunar soils are unknown among meteorites.

LITHIC FRAGMENTS IN CHONDRITIC BRECCIAS

1. Enstatite chondrites: sole example Abee [27], although Hvittis may be brecciated (my observ.). Cm-sized enstatite chondrite clasts, rimmed by Fe,Ni, have mineral compositions identical to those of the matrix but variable mineral abundances. Dark inclusions (mm-sized) are finer-grained, CaS and REE rich, but clearly of enstatite chondrite parentage [123, 139].

2. Ordinary chondrites: Abundance of brecciated H, L and LL group chondrites is 25, 10, 62 %, respectively [168]. Each group is dominated by lithic fragments of its respective compositional group, frequently of varying petrologic grade and embedded into finer-grained, often less equilibrated material of ordinary chondrite parentage. Mixtures of fragments of different groups are exceedingly rare and occur only in the LL chondrite St. Mesmin (H clast) [28] and the H chondrite Dimmitt (LL5 clast) [124]. A melt rock clast of L parentage was found in the LL chondrite Paragould [43] and one of H parentage in the LL chondrite Ngawi [40].

a) H breccias. Xenoliths: C2-CM clasts [1], mineralogy [41,47,52,124, 148, 169], O-isotopes [23,160], noble gases [157,160], trace elements [139], some transitional C1-C2 [41,94] or unusual type [112], some devolatilized [47], some indicate extraterrestrial aqueous alteration prior to breccia agglomeration [74]; fragment in Tieschitz [85] may be Huss matrix [71].

Clasts of new type of unequilibrated ordinary chondrite, with heterogeneous olivine and pyroxene in submicron intergrowth of graphite-magnetite matrix [124,125,136,137]. Graphite-magnetite clasts, up to 1mm [124,137,138]. Unusual chondrite clast [94]. Cognate clasts: Melt breccia fragments, formed by impact melting of host material and fractionation of Fe,Ni and FeS, sometimes contain clastic debris [39-43,45,47,48,73,74,77,159], mostly light-colored, sometimes round and mistaken for large chondrules [8]; types: microcrystalline [45], poikilitic [47], microporphyritic (olivine in glass/microcrystalline material) [14,41,74,111,159], skeletal olivine in high-SiO_2 glass (spinifex-texture) [42,55], clast-laden (clasts in igneous olivine-glass matrix) [41,48]. Somewhat impact-fractionated dark clast [94]. Clasts of H3 [41,111], H4 and H5 chondrites [10,111,112,124]. Shock-blackened pseudofragments [41].

b) L breccias. Xenoliths: C2-CM clast [148] is possibly a shock-melted clast [139]. Graphite - magnetite clasts [137]. Clast of CIII or unequilibrated ordinary chondrite parentage (possibly a new type) [44]. Cognate clasts: Melt breccia fragments [126,148]. Clasts of L3-6 [68] and L4 [148] type.

c) LL breccias. Xenoliths: New carbonaceous chondrite type [62,65]. K-rich ($\sim$1.5% K_2O) microporphyritic clasts [43,46,50,54,78,113]. Cognate clasts: Melt breccia fragments: Poikilitic [19,40,43], skeletal [19], aphanitic [19], microporphyritic [8,28,43,89]; rich in Fe,Ni+FeS [43]. Breccia clast [19]. LL7 clast [28]. Shock-blackened pseudofragments [28,43].

3. HL breccias (CV3,CO3). Xenoliths: C2 clasts, up to several cm in size, in Leoville [75]; "basaltic" fragments in Lance [86,87].

4. C2 breccias. Xenoliths: Carbonaceous chondrite type III clasts [57]. Clasts and xenolith [56].

REGOLITH BRECCIAS formed by shock lithification [2,80] of unconsolidated, impact-produced fragmental debris on or near the surfaces of parent bodies. They are prominent among H,L, and LL ordinary chondrites. The sole brecciated enstatite chondrite Abee and the CV3 Leoville are not regolith but fragmental and primitive breccias, respectively, whereas the gas-rich C2 Murchison may be a regolith breccia with foreign rock clasts [57]. Other C2's are gas-rich but appear to have only mineral fragments. The following discussion is therefore relevant mostly to ordinary chondrite regolith breccias.

Most have a characteristic light-dark structure whose origin was first ascribed to shock by [49]. They consist of cm- to sub-mm-sized, angular to rounded, generally equilibrated and recrystallized fragments embedded in a dark-colored, fine-grained matrix [49,74,88,93,111,162]. This matrix may be less equilibrated (type 3-4) than the light clasts as, for example, in Tysnes Island [74], Dimmitt [124], Plainview [41] and Weston [111]. Alternatively, the matrix may be as equilibrated as the clasts, such as in Pantar [49] and Nulles [Rubin, pers. comm.]. Intermediate cases may also exist, such as Rio Negro [44.]

Fine-grained silicate ("Huss") matrix [71] has not been found in regolith breccias. Grain sizes in regolith breccias are coarser than lunar ones [170], indicating that the former represent less mature regoliths. The matrices contain xenoliths (mostly carbonaceous) and cognate melt rock fragments of diverse textures (see above). The dark color is due to the fine grain size and possibly to the presence of carbon [4, 109,162] which by some is attributed to fine-grained debris of carbonaceous chondrite parentage [156-158]. Discovery of graphite-magnetite clasts and fragments of a new unequilibrated ordinary chondrite with a graphite-magnetite matrix in the matrices of many regolith breccias suggests that fine-grained debris of this composition may also be a major source of carbon [104,136-138]. Other bulk compositional differences between matrix and clasts are the higher volatile element contents in the former that approach those of unequilibrated ordinary chondrites [3,105,109].

Convincing evidence for a regolith origin comes from the contents of solar wind implanted light noble gases in the dark portions (^{4}He !1x10^{-5} to 2.2x10^{-2} cc/g STP) [127]. These gases were discovered in the achondrites Pesyanoe [59] and Kapoeta [167], and the finding that they are located exclusively in the dark portions of achondrites and chondrites [82,83] led to the suggestion that they may have been implanted by shock [49]. However, the gases are located in the outermost layers of mineral grains [33-35, 67,106,140,144,166], suggesting that they were incorporated by solar wind [144,151]. Many, but not all (e.g. L'Aigle), light-dark structured chondrites are gas rich; possibly some may never have acquired them or lost them due to reheating (e.g. due to deep burial). However, I consider all stones which are petrologically similar to those described above as regolith breccias. Note also that not all solar wind bearing chondrites are typical regolith breccias (e.g. the primitive breccia Bremervorde; Scott and Taylor, this vol.).

Further equally strong evidence for a regolith origin comes from the presence of solar flare tracks in individual clasts and mineral grains in the dark portions that sometimes indicate asymmetry of irradiation due to partial burial of grains during irradiation [91,92,96,101,102,117,119,130, 155,161]. Broken mineral grains require about 10^4 yrs. of irradiation between fracturing and compaction into a breccia [101]. Additional but less unequivocal evidence comes from the brecciated nature of the rocks and occurrence of impact-produced melt rock fragments and of carbonaceous xenoliths (residues of impacting projectiles), and of exceedingly rare agglutinates [79,111]. Agglutinates (and their devitrification products), glass spherules and impact glasses are very rare in chondrites (rare agglutinates and glass spherules were found in achondrites) [16,110,120], unlike lunar soil and regolith breccias. This could be due to the relatively low average impact velocities (and small crater size) in the asteroidal belt (which results in the production of very little melt), the immature nature and ultramafic composition of chondritic regoliths. Note that, although melt rock clasts are commonly found in chondrites, they are of low volumetric abundance (~3% in Dimmitt) [124], suggesting that impact melt production and/or retention on chondrite parent bodies was limited.

<u>FRAGMENTAL BRECCIAS</u> consist of clastic material (rock and mineral fragments) and sometimes melted material of the same composition but did not reside in regoliths for any length of time. Thus, they are devoid of typical regolith features, i.e. they never acquired solar wind implanted gases, solar flare tracks, agglutinates, etc. Many LL group chondrites (e.g. Siena) [40,43,89,100] are fragmental breccias with or without cogenetic melted material. Fragmental breccias may have formed by one or very few impacts that brecciated and melted the rock and buried it to depths below the active regolith zone. Alternatively, fragmental chondritic breccias may have formed during accretion or by disruption and reassembly of asteroidal-sized parent bodies (see below).

<u>IMPACT MELT BRECCIAS</u> have igneous matrices and may contain variable amounts of clastic, unmelted debris. Four types are recognized among chondrites. <u>1.</u> Impact melt rocks lacking clasts exist only as lithic fragments in regolith, fragmental and primitive breccias, not as individual stones. They are up to a few cm in size, light-colored, often depleted in Fe,Ni and FeS as a result of fractionation during impact melting, and have quench, spinifex,

microporphyritic and poikilitic textures (see "Lithic fragments in chondritic breccias"). They occur in H chondrites [39] such as Abbott [47], Dimmitt [124], Eva [42], Oro Grande [45], Plainview [41,77], Pulsora [55], Supuhee [94], Tysnes Island [74,159] and Weston [111,112]; in L chondrites [39] such as Bovedy [126], Dubrovnik [68], Lanzenkirchen [88] and Mezo-Madaras [148]; and LL chondrites [73] such as Bhola [43,46,54,113], Jelica [43,46], Kelly [19], Krahenberg [50], Ngawi [43,46], Siena [43,46,89], Soko-Banja [43,46], St. Mesmin [28,43,46] and others [43]. 2. Impact melt breccias with clasts occur as light-colored lithic fragments in the regolith breccias Adams County [48] and Plainview [41]. 3. Impact melt breccias with clasts that occur as individual chondrites include Shaw [133,147] and possibly Point of Rocks and Chico (our unpublished work). 4. Impact melt breccias in which black, shock-melted veins cut through unmelted, generally light-colored clastic material. Black veins were shown experimentally to form by shock [51] and consist of glass, quench crystals, Fe,Ni-FeS globules, residual, unmelted grains [15,76,168] and sometimes contain the high-pressure phases ringwoodite [12,13] and majorite [142]. They vary in their content of shock-melted material, even within a given hand specimen, and melting may be local or may involve injection of melt from some distance (e.g. Walters).

GRANULITIC BRECCIAS are metamorphosed fragmental breccias that are either polymict or monomict. Some equilibrated LL chondrites may be examples [43,98]. Granulitic breccias consist of rock and mineral fragments with granulitic and granoblastic textures. They must have been buried to considerable depths (tens of km) after brecciation and at a time when the temperature of the parent object was still sufficiently high to account for the texture. Thus, these breccias may have formed near the surfaces of small (tens of km) planetesimals that were buried to greater depths during agglomeration into larger objects [135]. Alternatively, they may have formed near the surfaces of larger objects (hundreds of km diameter) that were disrupted by large impacts and were buried to greater depths during reassembly [Rubin et al., this vol.]

PRIMITIVE BRECCIAS are ordinary chondrite breccias composed almost entirely of primitive components found in type 3 chondrites, including well-preserved chondrules, opaque and recrystallized fine-grained "Huss" silicate matrix, and clasts of type 3-6 chondrites, carbonaceous and impact-melted material [Scott and Taylor, this vol.]. They may have formed inside parent bodies by mixing of rock fragments with unconsolidated, primitive material during disruption and reassembly of asteroids.

TIME AND DURATION OF BRECCIA FORMATION. Dating the time of breccia formation is important because it allows inferences to be made to the duration of regolith and impact processes on meteorite parent bodies. Most ages were measured on melt rock clasts and glasses within gas-rich regolith breccias, i.e. rocks that have not been outgassed after agglomeration and compaction. Thus, ages of impact-produced materials set maximum limits on the time of regolith formation, i.e. the regolith formed more recently than the youngest clast. Such measurements were made on melt rock clasts from the howardites Kapoeta (ages of 3.5, 3.63, 3.89, 4.55 b.y.) [31,122] and Malvern (3.4-3.8 b.y.) [81], and on impact glasses from the howardites Bununu (4.24 b.y.) and Malvern (3.64 b.y.) [121]. Only 2 melt rock fragments from chondrites have been dated, a cognate clast in Plainview (3.63 b.y.) [77] and a K-rich xenolith in Bhola (not gas-rich) (3.65 b.y.) [113]. An H xenolith in St. Mesmin (LL) yields 1.36 b.y. [128, 129], and light and dark portions of Assam (L) give variable ages (3.6-4.5 b.y.) [131]. Fission tracks in phosphates are easily erased and, thus, allow dating of breccia formation which is >4.08 b.y. for Bhola [84], <4.30 b.y. for Weston, <4.25 b.y. for Fayetteville, and <4.28 b.y. for St. Mesmin [171]. Thus, although the bulk of the regolith may be ancient, rare, young clasts occur, indicating that regolith formation is an ongoing process on meteorite parent bodies.

PROCESSES OF CHONDRITIC BRECCIA FORMATION. Igneous rocks (e.g. achondrites, lunar rocks) formed by melting and differentiation in their parent bodies. Brecciated members can therefore not have formed by accretionary processes. However, chondrites are tuffaceous agglomerates that did not form by melting on a parent body and, hence, accretionary breccias (i.e. those that formed during agglomeration of their parent bodies) may exist. None have been recognized unequivocally, but some primitive breccias with coherent cooling rates [Scott and Taylor, this vol.] may be good candidates.

Regolith breccias formed by repeated impacts at or near the surfaces of their parent bodies, whereas fragmental, impact melt and some precursors to granulitic breccias formed by a single or at most a few major impacts and did not reside in a regolith for any length of time. Metallographic cooling rates [165] provide powerful evidence for another process of breccia formation, namely disruption of the parent body by a major impact and reassembly of the fragments into a rubble pile [Rubin et al., this vol.]. This process can also bury surface breccias to great depths or bring to the surface material from depth. Theoretical studies of the collisional evolution of asteroids suggest that break-up and reassembly of parent bodies is a viable process [25,26,63,64,69,70] and is supported by meteoritic evidence [Rubin et al., this vol.]. Cratering is incapable of bringing to the surface material from more than a few tens of km on a 200 km radius parent and, thus, disruption and reassembly of the parent object is the only alternative.

Regolith breccias with coherent and slow cooling rates and no solar wind gases (Bhola, 0.1 K/Myr) [135] must have formed at the surface and then been buried to great depth and may have formed by the same process. Similarly, granulitic breccias may have formed near the surface and been buried during disruption and reassembly of the parent body, although some may actually have formed altogether during the break-up-reassembly process. Note that disruption-reassembly may have occurred rather early in the history of the solar system, when temperatures of parent bodies were still sufficiently high to account for a cooling of the metal through the 700 K range.

Cooling rate measurements of some clasts in regolith breccias suggest repeated burial and excavation. For example, a melt rock clast in Dimmitt formed by impact melting on the surface, was buried to about 1 km depth, excavated, reincorporated into surface regolith, and consolidated into the regolith breccia [124].

SUMMARY AND CONCLUSIONS. 1. Among chondrites textural analogs to lunar regolith, fragmental, impact melt and granulitic breccias exist. Accretionary breccias do not exist on the moon nor among achondrites. 2. Chondritic breccias formed by repeated impacts in regoliths; single (or a few) major impacts; disruption and reassembly of parent bodies; and possibly accretion. 3. Disruption and reassembly of parent bodies is a viable and documented process for excavation from, or burial to, great depth. 4. Although similarities exist between chondritic and lunar breccias, important differences result from differences in cratering mechanics, impact velocities, melt production, composition, etc. 5. "Achondritic" lithic fragments in chondrites are not related to known achondrites but formed by impact melting and fractionation of host-like material. 6. Regolith formation occurred on meteorite parent bodies throughout the history of the solar system. 7. Some constituents of gas-rich regolith breccias were metamorphosed prior to consolidation. Grain-boundary heating due to shock is responsible for their compaction [2,80]. 8. H,L, and LL chondrites come from compositionally homogeneous, separate parent bodies. Materials of different petrologic grade exist near their surfaces; onion-shell structured parent objects [24] are not required. 9. Existence of gas-rich regolith breccias with homogeneous matrix minerals identical in composition to those of the equilibrated light fractions indicates that large areas must exist on parent body surfaces that are uniform and consist of equilibrated material only. Apparently, the regolith in those areas was of local origin, with little mixing of material of different petrologic grade from other, laterally and/or vertically distant sources.

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ROUNDNESS AND SPHERICITY OF CLASTS IN METEORITES, LUNAR SOIL BRECCIA, AND LUNAR SOILS.

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INTRODUCTION AND RATIONALE

One way to compare the accretionary processes of meteoritic breccias, lunar soil breccias and lunar soils is to take a sedimentary petrologic approach and compare the textural parameters of the clasts in the breccias and in the soils. Sphericity and roundness are two aspects of particle shape which is a textural parameter. Sphericity is a measure of the degree to which a particle approaches a spherical shape, whereas roundness is a measure of the sharpness of the corners and edges of a particle (Blatt et al., 1980). Clearly, sphericity and roundness are expressions of the external morphology of a particle. We argue that the external morphology of clastic particles is primarily dominated by the fragmentation processes, despite the fact that the morphology could be modified by subsequent secondary processes e.g. diagenesis in terrestrial sediments (May, 1980). Because of such secondary modification, it is difficult to infer the original fragmentation processes by interpreting the shape parameters of terrestrial sedimentary particles although it may be relatively easy to quantify sphericity and roundness (Barrett, 1980).

Regolithic particles on the moon and the meteoritic parent bodies owe their origin to impact shattering which tend to produce very angular non-spherical particles. Whereas very large impacts can produce melt sheets, very small impacts probably help only in gardening the uppermost regolith layer. Incorporation and transportation in any turbulent melt may cause resorption of the corners of the clasts and attainment of a near-spherical shape; splash of a small amount of melt may also wrap itself around a clast to produce a relatively well rounded and perhaps somewhat spherical a particle. Some agglutinitic glass would be examples of the latter phenomenon. Simple gardening is expected to provide some abrasion to round off some of the corners of clastic particles. We believe that the distribution of impact sizes, for a given regolith thickness, is likely to control the distribution of shape parameters.

In this abstract we present the results of a preliminary shape characterization study of 5700 particles (30-600μm) from ten gas rich meteorites, one lunar soil breccia (61295), and three impregnated soil samples from Apollo 15 drill core 15003. At present, no data of this kind are available and we believe that our data, preliminary as they are, can provide a framework for planning further studies.

METHOD

Polished thin sections of all the samples were used to take several sets of paired photomicrographs of each sample in transmitted and reflected light. Enlarged projections of these photomicrographs provided convenient maps of clastic particles. We used the traditional method of visual comparison to quantitatively estimate the roundness and sphericity of each clast (Krumbein and Pettijohn, 1938; Folk, 1968). The method is fast but lacks precision for several reasons. However, the method is adequate for the purpose of our pilot study: (a) to obtain the first data on particle shape of clasts in meteoritic breccias, lunar soil breccias, and lunar soils, and (b) to estimate the degree of rigour necessary in future measurement procedures.

RESULTS AND DISCUSSION

Results of our measurements are given in Table 1. In general, the re-

Table 1. Distribution of shape parameters of clasts in selected meteorites, lunar soil breccia 61295, and lunar drill core soil 15003. All values expressed as percents of total number of measurements.

	Roundness					Sphericity				n	X100	
	0.1	0.3	0.5	0.7	0.9	0.3	0.5	0.7	0.9		Rd	Sp
Meteorites												
Nobleborough (Eucrite)	4.7	34.7	44.7	14.3	1.7	39.7	45.3	13.3	1.7	300	45	45
Pesyanoe (Eucrite)	4.3	49.7	38.3	7.0	1.3	28.7	37.0	23.7	10.7	300	41	53
Johnstown (Diogenite)	2.3	38.7	51.3	5.7	2.0	30.7	43.7	19.0	6.7	300	43	50
Roda (Diogenite)	1.7	48.0	44.7	4.7	1.0	43.0	39.7	15.0	2.3	300	41	45
Khor Temiki (Aubrite)	5.3	44.3	40.3	8.0	2.0	35.3	35.7	22.0	7.0	300	41	50
Frankfort (Howardite)	1.7	34.0	52.7	10.0	1.7	43.0	39.7	15.0	2.3	300	45	45
Pavloka (Howardite)	4.3	47.2	35.0	11.7	1.8	50.7	38.7	9.7	1.0	600	42	42
Luotolux (Howardite)	2.8	54.0	36.0	5.3	1.7	48.3	39.7	10.2	1.8	600	40	43
Le Teilleul (Howardite)	2.2	38.0	50.3	9.7	1.5	37.3	45.5	14.3	2.8	600	45	46
Bununu (Howardite)	4.7	39.8	44.5	9.3	1.7	30.5	34.5	24.0	11.0	600	43	53
Lunar Soil Breccia 61295	3.5	44.8	41.7	8.0	2.0	24.0	39.6	27.5	9.2	600	42	55
Lunar Soil 15003,--												
6055	9.7	50.0	35.3	3.7	1.3	37.3	34.0	22.7	6.0	300	37	49
6056	15.3	30.7	37.3	12.3	4.3	29.7	35.7	28.7	6.0	300	42	52
6059	11.7	38.7	36.7	9.3	3.7	37.3	32.0	23.3	7.3	300	41	50

Average	*Howardites*	*Lunar Soil Breccia 61295*	*Lunar Soil 15003*
Roundness	*0.43*	*0.42*	*0.40*
Sphericity	*0.46*	*0.55*	*0.50*

sults show that there is little systematic variation of roundness and sphericity values of the samples. In fact, there is not less variation between individual meteorites than there is between meteorite classes, lunar soil breccia, and lunar soils. However, a comparison between the average roundness and sphericity values of clasts in howardites, lunar soil breccia, and lunar soils reveal a subtle trend of decreasing roundness (Table 1). The trend may possibly indicate the different degrees of abrasion undergone by the particles in their history. Clasts in howardites show the least sphericity whereas those in lunar soil breccia 61295 provide the highest values. We interpret the data to suggest that the clasts in 61295 have been involved in melting events more than those in howardites or in lunar soils. A possible, but perhaps fortuitous, support of this interpretation comes from Bununu. It is the only howardite with known agglutinates which imply melting events (Rajan et al., 1974; Basu and McKay, 1981). The sphericity of the clasts in Bununu is the highest of all the meteorites studied (Table 1). However, our methodology has low precision and, therefore, our interpretations are tentative at best at this time.

The data, interpreted in the light of our rationale narrated earlier, suggest that there is enough reason to proceed further with more precise measurements of shape parameters. We propose to perform Fourier grain shape analyses of computer-digitized maps of the clasts in different kinds of accretionary materials of the solar system. Such analyses will provide data on the size, shape, and possibly also on the packing of clasts in parent body regoliths.

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EVOLUTION OF AN ASTEROIDAL REGOLITH : GRANULOMETRY, MIXING AND MATURITY.

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INTRODUCTION

The strongest argument in favor of thick asteroidal regoliths is the large proportion of meteorites which are breccia (50 to 100% depending on class) and, among these breccia, the significant proportion of gas-rich meteorites. Housen (this volume) discusses the models of regolith formation on an asteroid as a function of its size and the cohesive strength of its substrate. However, in these models (Housen et al, 1979 ; Langevin and Maurette, 1980) ,"regolith" designed anything extracted by craters from the bedrock. It could apply to a pile of boulders ("megaregolith") just as well as to a true, fine-grained regolith. I will thus discuss in this paper the characterisitcs and evolution of the material constituting an asteroidal regolith : size distribution of the source material, and processes that may modify it ; vertical and lateral mixing processes, which determine the irradiation history of the constituents, and thus the "maturity" of asteroidal regoliths. These results will be compared with the actual characteristics of meteoritic breccias.

It should however be noted that most meteoritic breccias (in particular C1 and C2 chondrites) are very old objects (see Bogard, 1979) , having been formed during the accretion - post accretion period (4.5 to 4 b.y. ago) . Unfortunately, parameters such as the total flux, mass and speed distribution of meteoroids are completely unknown during this period, thus preventing any modeling events. However, at least some meteoritic breccias have compaction ages younger than $\sim$ 3 b.y. ago (Bogard, 1979) . I will thus try to describe what has happened on the surface of asteroids since 3 b.y., a period during which meteoroid and charged particle fluxes have been constant within a factor of 3, as demonstrated by lunar studies. I will rely as much as possible on evidence from the well documented lunar regolith.

I. GRANULOMETRY ON ASTEROIDAL REGOLITHS

On the Moon, fresh regolith material comes from large craters ($\sim$ 200 m) in the bedrock. The size distribution of this population can be inferred from nuclear craters (Frandsen, 1967) , the presence of blocky rims (Moore, 1971), or the thermal signature (Schultz and Mendell, 1978) . It is extremely coarse: 50% of the mass is deposited as fragments more than 10 cm in size. Hörz et al. (1975) have shown that fragmentation by a direct micrometeoroid impact is a very efficient process on the Moon, reducing the mean graphic size from $\sim$ 10 cm to less than 100 µm in a fraction of the available exposure time ($\sim$ 100 000 y). Shock comminution of grains in craters much larger than their size (Stöffler et al., 1975) is a relatively minor process on the Moon. Glassy agglutinate formation is on the contrary quite active ($\sim$ 50% of the volume) and depletes the smallest size fractions (< 10 µm ; Morris, 1978) . Finally, the grain size distribution observed on the Moon is well accounted for by these three processes (Langevin and Maurette, 1981) .

Let us now consider a basaltic asteroid. The gravity g is $\sim$ 4 cm.s^{-2} for a size of 100 km. Ejecta from km-sized craters spread over very large regions, and constitute the dominant contribution to regolith growth (see Housen, this volume) . In flight comminution and interaction with secondary ejecta result in a size distribution similar to that of smaller bedrock craters (Shultz and Mendell, 1978) .

A completely different source has been proposed by Hörz and Schaal(1981): large impacts spall material from the rear surface of small bodies, with much higher yields than direct cratering. However, the median size of the platy spall fragments is ~ 0.1 times that of the asteroid itself (Fujiwara et al., 1977) . I prefer to consider these events on a 1 to 10 km scale as bedrock fractures, possibly generating grooves such as those on Phobos (Veverka and Burns, 1980) . They do not contribute directly to the regolith, but may enhance the yield of local large impacts, and modify the propagation of seismic waves in the asteroid.

Let us now evaluate the 3 major processes which modify the size distribution of constituents. The flux of very small meteoroids ($\gtrsim 10^{-9}$ g) decreases by a factor of 5 in the asteroidal belt (Humes et al., 1974) . This population has thus probably a cometary origin, with impact velocities ~ 15 km/s, as opposed to ~ 25 km/s at 1 a.u. . The efficiency of the fragmentation process should be ~ 10 times lower than on the Moon. Conversely, large meteoroids have probably an asteroidal origin (e.g. Anders, 1975) , and their flux should be much larger in the source region. The mixing rate is higher, and the mean exposure time shorter by at least a factor of 30 (see part II) . Therefore, fragmentation events should occur for less than 3% of the regolith constituents (Langevin and Maurette, 1981) . On the contrary, the efficiency of shock comminution is proportional to the large scale cratering rate, and thus to the mixing rate. 1 to 2 comminution events are expected for a typical constituent, each reducing the mean size by a factor of ~ 10 (from Stöffler et al., 1975) . This process, contrarily to the fragmentation process, does not require a direct surface exposure. Consequently, the correlation between grain size and maturity indices should be much weaker in an asteroidal regolith than on the Moon. Agglutination, which is induced by micrometeoroids on the smallest size fraction, becomes quite negligible. As a conclusion, the mean graphic size in the regolith of a basaltic asteroid should be much coarser (~ 1 mm) than on the Moon.

On weaker C-type asteroids, the initial size distribution of ejecta from the bedrock is probably fine grained. The comminution process is very effective, as the shock pressure required to shatter C-type material is at least 3 orders of magnitude lower than in basalt. C-type regoliths should thus be very fine grained, although an evaluation of the mean size is not possible.

How do these results compare with the size distribution of grains in meteoritic breccia ? Ordinary chondrites and achondrites are indeed depleted in grains less than 70 μm in size compared to lunar breccia. Furthermore, there is no clear difference between gas-rich and non gas-rich meteorites (Bhattacharya et al., 1975) . However, the graphic mean size (~ 100μm) is only ~ 2 times higher than in the lunar regolith. This discrepancy between the predicted and observed mean sizes suggest that asteroidal bedrocks are weaker than basalt.

Another difficulty arises from the low shock lithification yield measured by Stöffler et al. (1975) for 6 km/s impacts into quartz sand : the very high proportion of breccia among meteorites cannot be explained by small scale regolith cratering. This apparent contradiction may be solved in two ways :

i) Very large craters in a regolith should have a higher shock lithification yield than smaller craters : For craters deeper than ~ 100 m, porous materials have a Mohr-Coulomb behavior (see O'Keefe and Ahrens, 1981) , characterized by progressively higher yield strains, and smaller cratering efficiencies. The highly shocked region then represents a larger fraction of the displaced volume.

ii) During the post-accretion period, very large impact rates should have resulted in the formation of megaregoliths similar to, but thicker than the km thick megaregolith which underlies the lunar highland (Hörz et al.,1976) . Part of the meteoritic breccias could then originate from the megaregolith of the asteroids.

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II. REGOLITH MIXING ON AN ASTEROID

The most important parameters for regolith mixing are the same as for regolith formation : the mass and speed distributions of meteoroids in the belt, the scaling relations linking the impacting mass and speed to the volume of the resulting crater, and the speed distribution of ejecta. From orbital dynamics, an impact speed of ~ 5 km/s is generally assumed. The mass distribution has not been directly measured. It is expected to follow a power law relationship, $\Phi(>m) \propto m^{-\gamma}$, with $\gamma \sim 0.8$ to 1 (Dohanyi, 1972, 1976) .

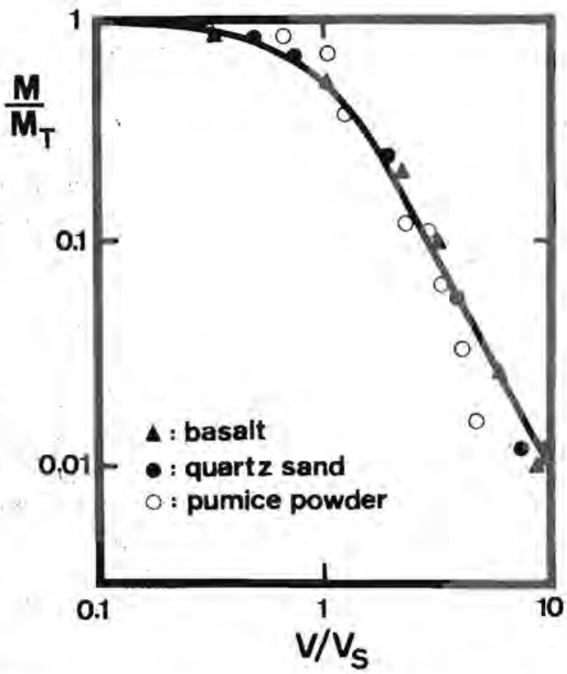

Figure 1 : fraction $\gamma(V)$ of ejecta with a speed >V, as a function of V/V_S, where V_S is the median speed ($\gamma(V_S) = 0.5$) . The solid curve represents the model relation : $\gamma(V) = 1/((V^2/V_S^2) + 1)$

The speed distribution has been measured in basalt (Gault et al., 1963) , quartz sand (Stöffler et al., 1975) and pumice powder, a close rheologic analog to the lunar regolith (Hartmann, 1981). It is remarkably similar in all three materials, when normalized to the median speed V_S (~ 60 m/s, 1.1 m/s and 0.5 m/s in basalt, quartz sand and pumice powder respectively ; see fig. 1) . A simple model, assuming that a constant part of the available mechanical energy is spent in overcoming the cohesive strength (for craters less than ~ 100 m deep ; see O'Keefe and Ahrens, 1981) leads to the relation : $\gamma(V) = 1/((V^2/V_S^2) + 1)$, which is in good agreement with the experimental data. V_S^2 scales approximately as S/ρ, where S is the cohesive strength and the density (in agreement with the model of Ivanov (1976)), although the dynamic tensile strength may be a more appropriate parameter (O'Keefe and Ahrens, 1981).

When the radius R of the crater exceeds the median range, $R_S = V_S^2/g$ (ejecta are thrown at a 45° angle ; Stöffler et al., 1975) , a large proportion of ejecta fall within the crater, thus reducing its size. Two distinct relations hold when $R < R_S$ (strength scaling) and $R > R_S$ (gravity scaling of the final crater ; gravity scaling of the transient crater occurs only at very large scales ; see O'Keefe and Ahrens, 1981) . In the strength scaling region, R scales as $m^{1/3}$, where m is the impacting mass. It has been shown (e.g. Gault and Wedekind,1977) that R scales as $m^{1/3.5}$ for gravity scaled craters, which exhibit well developed ejecta blankets. Equaling these relations at $R = R_S = V_S^2/g$ for any value of V_S and g leads to the relations :

$$R \sim \left(\frac{\alpha m}{\rho V_S}\right)^{1/3} \quad \text{(strength)} \qquad R \sim \left(\frac{\alpha m}{\rho\sqrt{g}}\right)^{1/3.5} \quad \text{(gravity)}$$

This $g^{-0.142}$ dependence derived from a dimensional analysis is indeed close to the $g^{-0.165}$ dependence measured by Gault and Wedekind (1977) or the $g^{-0.158}$ dependence observed by Schmitt and Holsapple (1980) in centrifuge experiments. The value of α for impacts at 5 km/s can be derived from the crater volumes observed in basalt and quartz sand, and is $\sim 2.10^6$ CGS. The resulting distribution of ejecta blankets exhibits a steep change at a thickness $h \sim R_S/10$:

$$N(>h) \propto h^{-(3\gamma-2)} \quad (h < R_S/10) \qquad N(>h) \propto h^{-(3.5\gamma-2)} \quad (h > R_S/10)$$

We can now compare regolith mixing on bodies of different size simply by noting that the thickness distribution N (>h) of ejecta blankets and the depth distribution of craters stay the same, if R_S is selected as the unit of length, and $\tau \propto K^{-1}.R_S^{(3\gamma-2)}$ as the unit of time, where K is the relative efficiency of meteoritic cratering on the body. The deposition rate varies as $\sim K.R_S^{(3-3\gamma)}$. *In particular, on the Moon,* $V_S \sim 0.5$ *m/s, and* $R_S \sim 15$ *cm, whereas on a 100 km* basaltic asteroid, the regolith is coarser, $V_S \sim 1$ m/s and $R_S \sim 20$ m. If we assume $\gamma \sim 0.9$ in both cases, a value of K ~ 30 times larger on the asteroid would decrease the mean exposure time by a factor $\gtrsim 100$, proposed by Anders (1975) on the basis of solar wind contents in gas-rich meteorites. On the 100 km asteroid, regolith mixing and deposition would occur 2 times faster than on the Moon, at a 40 times larger scale. Monte-Carlo models have shown that on the Moon, a typical event is the deposition of a $\sim$ 3 cm thick ejecta blanket, which develops a $\sim$ 5 mm thick "skin" well mixed by strength scaled craters, before being covered by a new blanket 25 m.y. later. This translates on the asteroid as a $\sim$ 1 m thick layer, developing a $\sim$ 20 cm thick "skin" in $\sim$ 12.5 m.y.. This scenario is remarkably similar to that proposed by Lorin and Pellas (1979) for the Djermaia H-chondrite.

Two processes playing a minor role on the Moon may modify this description :

i) downslope ballistic transportation results from the greater range of ejecta headed downslope, resulting in a net downward displacement of the center of gravity of ejecta (Arnold, 1975 ; Young, 1979) . Being due mostly to strength scaled craters, the efficiency of this process is proportional to R_S, thus much larger on small bodies than on the Moon. From the detailed discussion of Langevin, Nishiizumi and Arnold (1981), the lifetime of a 100 m crater should be only $\sim$ 30 m.y. on a 100 km asteroid. The timescale of the process increases as the square of the linear scale, and it can redistribute regolith material up to a scale of $\sim$ 1 km.

ii) seismic "shaking" of the whole regolith occurs on a strong body whenever a crater larger than $\sim$ 1/20 th of its size is formed (Schultz and Gault, 1978 ; Langevin and Maurette, 1981 ; Hörz and Schaal, 1981) . This process could occur 100 to 1000 times until the fragmentation of the asteroid. The main effects of such a process would be:a global vertical mixing of the regolith every few m.y., redistributing surface exposed grains from a $\sim$ 5 cm "skin" (Langevin and Maurette, 1981), which could bury selectively the smallest grains (Hörz and Schaal, 1981) ; a "vibrating table" lateral transport process, which would redistribute the regolith on a scale of $\sim$ 10 km.

III. MATURATION PROCESSES IN AN ASTEROIDAL REGOLITH

The exposure of grains near the surface results in a series of effects, such as solar wind implantation, Galactic and Solar cosmic ray tracks, and the formation of microcraters and agglutinates, which together define the maturity of a soil. For two of these processes, the variation with heliocentric distance is well known : galactic cosmic rays increase by only a few % from 1 to 3 a.u. (Owens, 1979), and the solar wind follows an inverse square law relation (Barnes, 1979) . The micrometeoritic flux ($m \lesssim 10^{-6}$g) is reduced by a factor of 5 in the belt. The situation is more complex for solar energetic particles, as two components are present : i) solar flare particles dominate at energies of $\sim$10 MeV/amu, and their flux drops by a factor of $\sim$ 20 between 1 and 3 a.u. (Zwickl and Webber, 1977). ii) corotating particles are accelerated in interplanetary shock waves, and their flux between 1 and 2 MeV/amu increases by a factor of $\sim$ 10 from 1 to 3 a.u. (McDonald et al., 1976) .

Precompaction galactic cosmic ray exposure ages are difficult to evaluate. However, Anders (1975) showed that the bulk solar wind gas contents correlated fairly well with estimated exposure ages, assuming a 100 to 1000 times higher burial rate than on the Moon. These high turnover rates, together with the low fluxes of solar wind ions and micrometeorites, well explain the observed scarcity of solar wind amorphous coatings, microcraters and glassy agglutinates. I will discuss in more details the particle track record of gas-rich meteorites.

Track densities are measured in 50 to 200 μm grains. Our scaling procedure suggests that the exposure history of such grains on a 100 km asteroid is similar to the exposure history of grains a few μm in size in the lunar regolith. Indeed, a scaled-up version of the Borg et al. (1976) model shows that only 1 grain out of ∿ 10 in the typical 1 m thick layer reaches the surface, staying there for 10^4 to 2.10^4 years. The expected proportion of track rich grains is thus on the order of 10%, up to 50% in the upper part of each layer, and the number of exposures of each 100 μm grain should be very low. These results are consistent with the proportion of track-rich grains observed in gas-rich ordinary chondrites (Lorin and Pellas, 1979), and achondrites (Poupeau et al.,1974; Bhattacharya et al., 1975), but are higher than those observed in C1 and C2 chondrites (Goswami and Lal, 1979) . This may be due to the weaker substrate of C-type asteroids, which increases the burial rate, or to free space exposure of the grains (see Rajan, this volume) . The small expected number of near-surface exposures is also consistent with the anisotropy of the track gradients observed in gas-rich meteorites (Price et al., 1975 ; Goswami and Lal, 1979), which suggests a single irradiation geometry for most of the track-rich grains.

However, two difficult problems arise :

i) the track density in track-rich grains ($\sim 10^8 t/cm^2$) is only a factor of 30 lower than typical high track densities in the lunar regolith, while the deposition rate is ∿ 100 times higher, and the flux of solar flare particles ∿20 times lower. This is due in part to the smaller fraction of grains which share the available exposure time. It could also result from a longer etchable range of Fe group tracks in meteorites, due to the partial annealing of lunar fossil tracks, or to exposure of grains at the surface of rocks, which could be as long as 100 000 y. .

ii) very steep gradients are expected in the outer 10 μm of track rich grains, as the corotating component has a steep energy spectrum, and the ratio of 1 to 10 MeV/amu ions increases by at least a factor of 5 between 1 and 3 a.u. . Although gradients in meteoritic grains tend to be steeper than in lunar grains (Price et al., 1975), such very steep gradients have not yet been observed. This could be due to a dust coating, which would screen the low energy particles, or to a partial destruction and/or shock annealing of the edges of the grains during the brecciation process.

CONCLUSIONS

Most of the characteristics of meteoritic breccias can be understood if they originate on medium-sized asteroids. The scale of regolith mixing processes is linked with the median range of ejecta, and is thus much larger on asteroids than on the Moon. The relatively fine granulometry of meteoritic breccias is difficult to understand if the bedrock of the parent asteroids is as strong as lunar mare basalt. More work is needed to quantitatively describe the brecciation process. Caution is required when comparing the models of present day asteroidal regolith evolution with the characteristics of objects with very old compaction ages, such as carbonaceous chondrites, as the meteoroid and particle environment during the first few hundred million years of the history of the solar system was certainly very different both in total flux and spectrum from the contemporary environment.

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SPACE EXPOSURE OF BRECCIA COMPONENTS, J.D. Macdougall, Scripps Institution of Oceanography, La Jolla, California 92093

The American Geological Institute Glossary of Geology suggests that, to qualify as a true breccia, a rock must contain ≥ 80% rubble. The object of this review, then, is to examine, from the point of view of exposure to solar flare, solar wind and micrometeorite particles, the history of the solar system rubble incorporated in meteoritic and lunar breccias. Emphasis will be given to the evidence for exposure of individual breccia components before consolidation, since information about the recent exposure of breccias as rocks in space, while interesting, is much less relevant to the nature and mode of formation of breccias. Not all meteoritic or lunar breccias contain evidence for pre-consolidation exposure, and this in itself is a useful area for comparison: which classes or petrographic types of breccia contain pre-consolidation exposure records and how do these divisions compare between moon and meteorites? In most of the discussion below, the lunar-meteorite comparison is implicitly restricted to breccias which do contain such records.

The physical evidence for pre-consolidation exposure of breccia components is in the form of tracks of solar flare particles in mineral grains, implanted and spallation produced species due to solar wind and solar flare bombardment, and craters on grain surfaces due to micrometeorite impacts. All of these features are sensitive to shielding, although to varying degrees. Their presence in breccia components requires exposure at shielding depths ranging from zero to about a meter of rocky material, and by analogy with the moon the exposure features in meteoritic breccia components are usually believed to have been produced in a regolith environment. However, this hypothesis appears to be inconsistent with the experimental data from some meteorites, especially the carbonaceous chondrites. This is an area of breccia studies where direct lunar-meteoritic comparisons can be made, and where careful examination of the experimental data should be able to resolve questions about the exposure conditions.

A second important aspect of exposure histories concerns the marked differences in the integrated exposure records in lunar vs. meteoritic breccias. On a grain-for-grain basis, virtually 100% of the components of "gas-rich" lunar breccias show evidence for exposure to solar flare and cosmic ray particles within a few cm of the lunar surface. For the gas-rich meteorite breccias this fraction rarely rises above ∿20%, and frequently is less than a few percent. In addition, the individual irradiated components in the meteoritic breccias generally have been less intensely bombarded than their lunar counterparts. Thus the duration of the irradiation of meteoritic components apparently was very short relative to the lunar case. This implies rather short-lived near surface regoliths on the meteoritic parent bodies, if irradiation occurred in a regolith. Other types of irradiation environment may also be consistent with the data. Exposure age data for some carbonaceous chondrites are consistent with very short irradiation times. For several CM meteorites with exposure ages $\leq 10^6$ yrs, exposure times based on ^{26}Al (i.e. recording the recent exposure of the meteorite as a small body in space) are essentially identical to those based on ^{21}Ne (i.e. integrating over both the recent space exposure and exposure of the breccia components at any time in the past).

A further important topic in the study of lunar and meteoritic breccias, and the irradiation of their components, is the question of the time of their exposure. Fission track studies of the CI and CM meteorites seem to indicate that the irradiation features observed in their components were acquired $\geq 4.2 \times 10^9$ yrs ago, and that they have remained essentially in their present state since that time (Macdougall and Kothari, 1976). In contrast, studies of basaltic clasts from the gas-rich howardite Kapoeta show that their internal radiometric systems were reset at times as recent as 3.6×10^9 yrs ago (Papanastassiou et al., 1974). Because the radiometric ages of other clasts range up to $\geq 4.5 \times 10^9$ yrs., it is at least possible that a regolith existed on the Kapoeta parent body for $\geq 10^9$ yr. Still, the irradiation features of Kapoeta components are considerably different from those of lunar gas-rich breccias and the lunar soil, and the fraction of surface-exposed material is relatively small, $\lesssim 20\%$. The gas-rich howardite Bununu also has components with radiometric ages considerably less than 4.6×10^9 yrs (Rajan et al., 1975), and these components could have been part of a parent body regolith for times ≥ 400 my.

The carbonaceous chondrites present some special problems. They are heterogeneous assemblages of components, and breccias in the sense of being agglomerations of diverse and often angular fragments. A large fraction is gas-rich: about 60% in the case of the CMs, and all CIs. If irradiation occurred in a regolith, then essentially the whole parent body must have been "regolith", or a random sampling would have yielded a much smaller fraction of gas-rich examples. This has led to a special model for irradiation of carbonaceous meteorite components (Goswami and Lal, 1979); this will be discussed separately (Rajan, this volume).

Finally, there is a still-unanswered puzzle concerning the irradiation of the components of some lunar breccias. A number of Appollo 14 breccias contain Xe from decay of the short-lived isotopes ^{129}I and ^{244}Pu (e.g. Drozd et al., 1972). It is usually inferred that the rocks themselves formed very early, $> 4 \times 10^9$ yrs. ago. At least one other breccia has a well-defined formation age of 3.69×10^9 yrs. (Alexander and Kahl, 1974). Some components of these breccias were heavily irradiated by solar flare nuclei prior to induration. Studies of lunar remnant magnetism, however, suggest that the moon possessed a substantial field at this time (Collinson et al., 1975), sufficient to prevent such bombardment of surface materials. The alternatives seem to be that consolidation of the breccias actually took place after the decay of the magnetic field, i.e. much more recently than 4 b.y., or that the magnetic field data are in error.

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PRIMARY STRUCTURES IN LUNAR CORES AND REGOLITH BRECCIAS; J. Stewart Nagle, Lunar Curatorial Laboratory, Northrop Services, Inc., P.O. Box 34416, Houston, Texas 77034.

Most of the fragile, cm-scale heterogeneities in unconsolidated lunar cores appear to be primary sedimentary structures because: (1) the features are too fragile to survive excavation and (2) the morphologies of these structures can be produced experimentally by ballistic deposition and avalanching, similar to lunar depositional processes (Nagle, work in progress). Lunar and meteorite regolith breccias catalogued by Ryder and Norman (1980), Score *et al*. (1981), and Carlson and Walton (1978) display some, but not all of these same structures observed in the cores. The absence of some of the features in soil breccias suggests that physical changes occur during breccia consolidation. An understanding of features that occur in the lunar regolith is only possible by examining lunar cores. This understanding is a prerequisite for determining what modifications occur during formation of soil breccias. The features described here were observed in the 4 cm drive tubes 15008/7, 15011/10, 60010/9, 64002/1 and 76001. The 4 cm drive tubes show the fewest mechanical disturbances during sampling, and are most likely to contain intact primary structures.

Core soils show two basic structure types: massive and marbled. Massive soils, primarily on the basis of color, appear homogeneous, and make up 70% of core soils. Marbled soils show very irregular areas of different color and texture, and compose the remaining 30% of core soils.

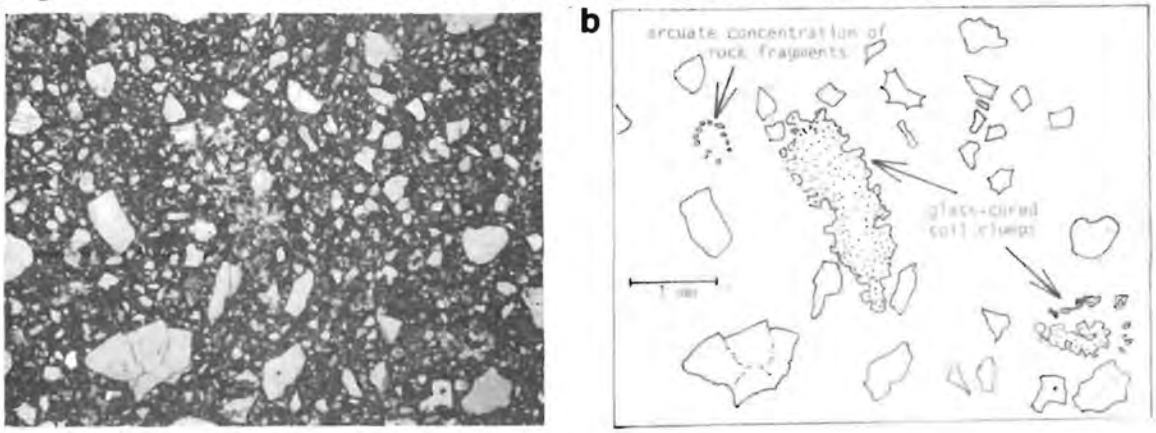
Massive soils are not necessarily homogeneous. They contain the following consistently recurring internal properties: (1) rock fragments of similar lithology occur in clumps, rather than being evenly or randomly distributed. (2) Aggregates of vesicular glass and attached soil breccia commonly occur in concentrations. All particles therein show a preferred orientation, with the glass on top and soil breccia below (Nagle, 1977, 1978, 1979a,b, 1980, 1981; Langevin and Nagle, 1980; Nagle and Waltz, 1979). (3) Glass cored soil clumps (Fig. 1A,B) and (4) radially arcuate soil clasts (Fig. 1C,D) appear to be present in all massive soils. Less commonly, massive soils contain clasts of light-colored soil, such as those in core sections 60009, 15007, and 64001. These friable soil clasts have relatively smooth, rounded margins (Fig. 1G,H) and are very different from the irregular soil clumps in marbled soils. Other minor features of massive soils include whitish horizontal comma shapes (Fig. 1E,F) and diffuse haloes of white granules surrounding sugary to chalky white rock fragments.

Marbled soils are heterogeneous on a mm- to cm- size scale. In marbled soils, patches of light and/or dark soil are not only different from the matrix, but show very irregular margins that may be crenulate, filamentous, or gradational, or a combination of the above. The most common type of easily-recognized feature in marbled soils is the radial-arcuate clump (Fig. 2A-D). This spiral-like feature is characterized by one or more arcuate lithologic zones radiating from a common center.

Comparison of marbled units reveals a consistent structural pattern, manifest as a succession of shapes of friable soil clasts. At the base of a typical unit, friable clasts are flattened horizontally. Higher in the unit, the radial arcuate form becomes prevalent, with all arcuate clasts coiled in the same direction. This morphological succession, which is illustrated in Fig. 3 (also in Nagle, 1981) occurs in most marbled units in 60010/9 and 64002, and in all the marbled units in cores 15008/7 and 15011 -- a total of nine out of 12 marbled units. At the base of marbled units in lower 60009 and mid-64002, are upward-protruding fingers of dark soil (Fig. 2E,F) in addition to flattened clasts. An exception occurs in the marbled unit that falls in both 64002 and 64001; the lowest clasts are well-rounded instead of

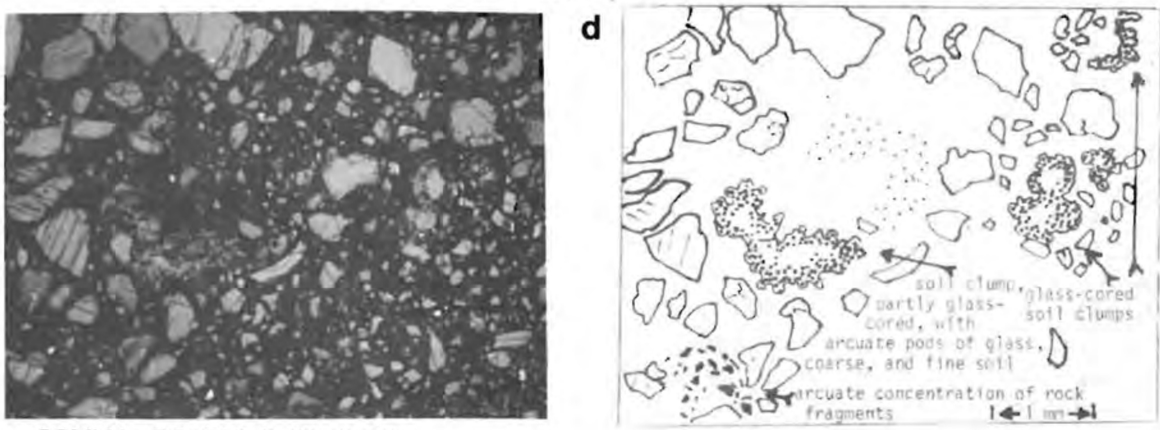
Fig 1 GLASS CORED SOIL CLUMPS IN 15008

a b



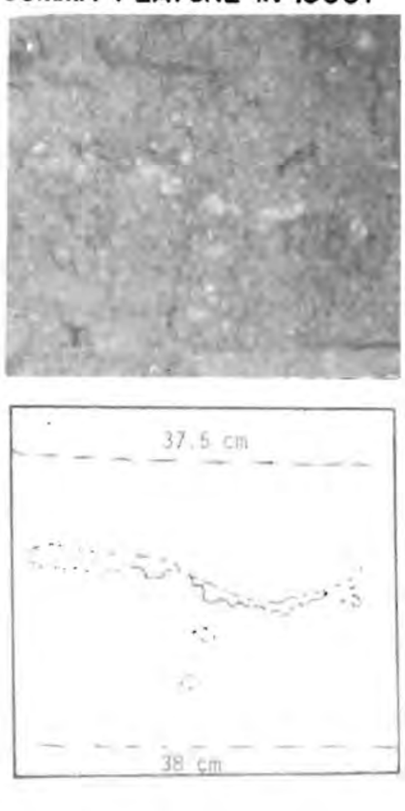
RADIAL-ARCUATE CLUMPS IN 15011

c d



COMMA FEATURE IN 15007

e f



ROUNDED CLASTS IN 15007

g h

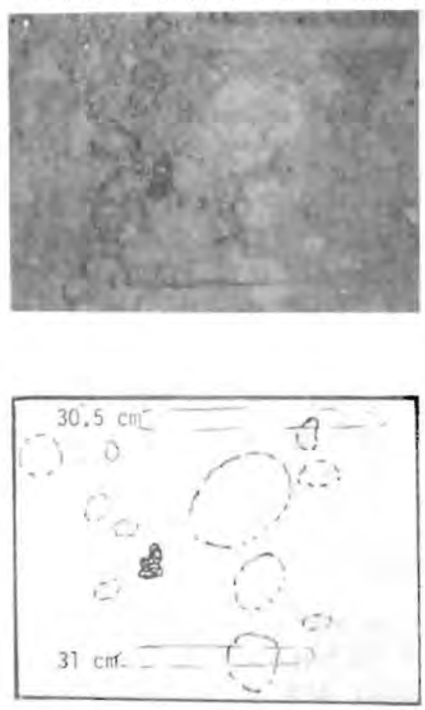
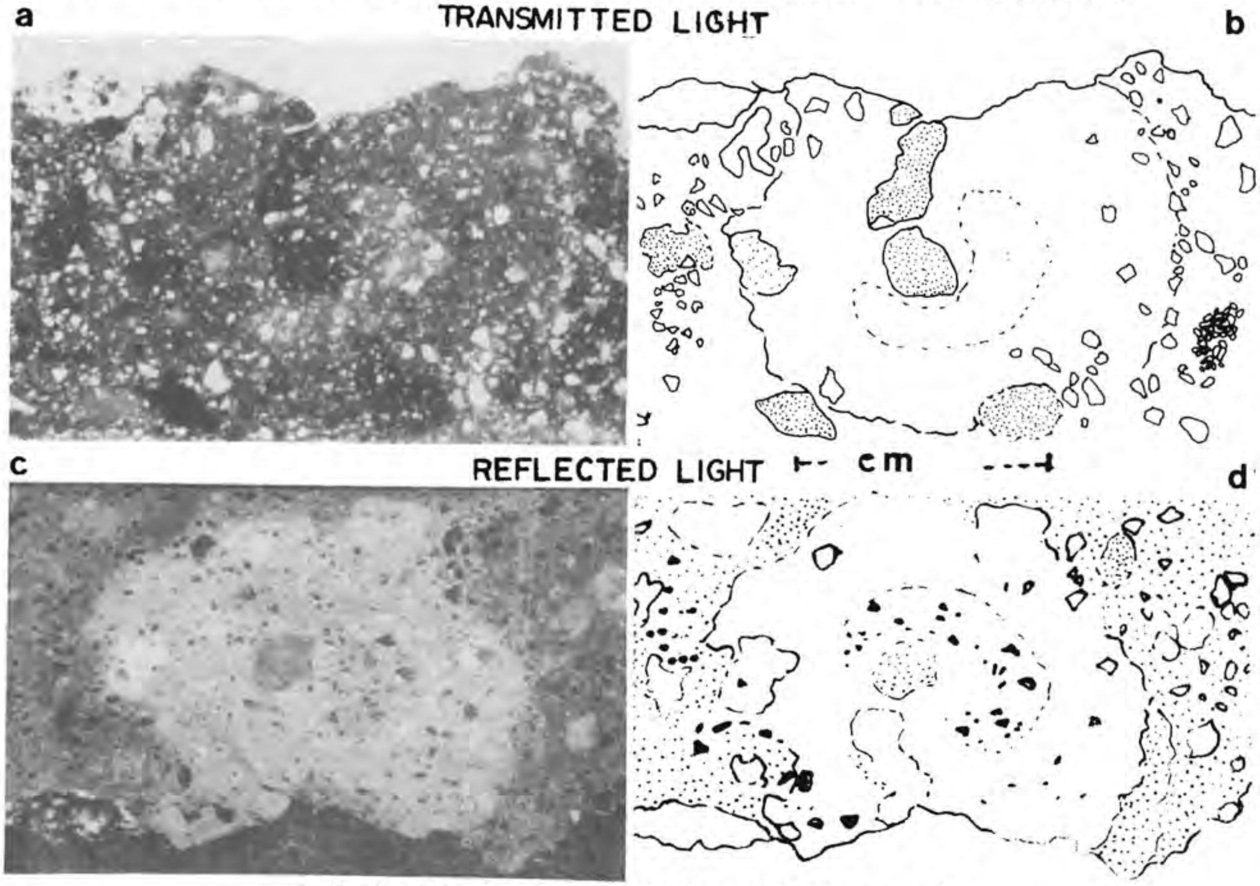


Fig 2 RADIAL ARCUATE SOIL CLUMP IN 60009



DARK FINGER OF SOIL IN 60009

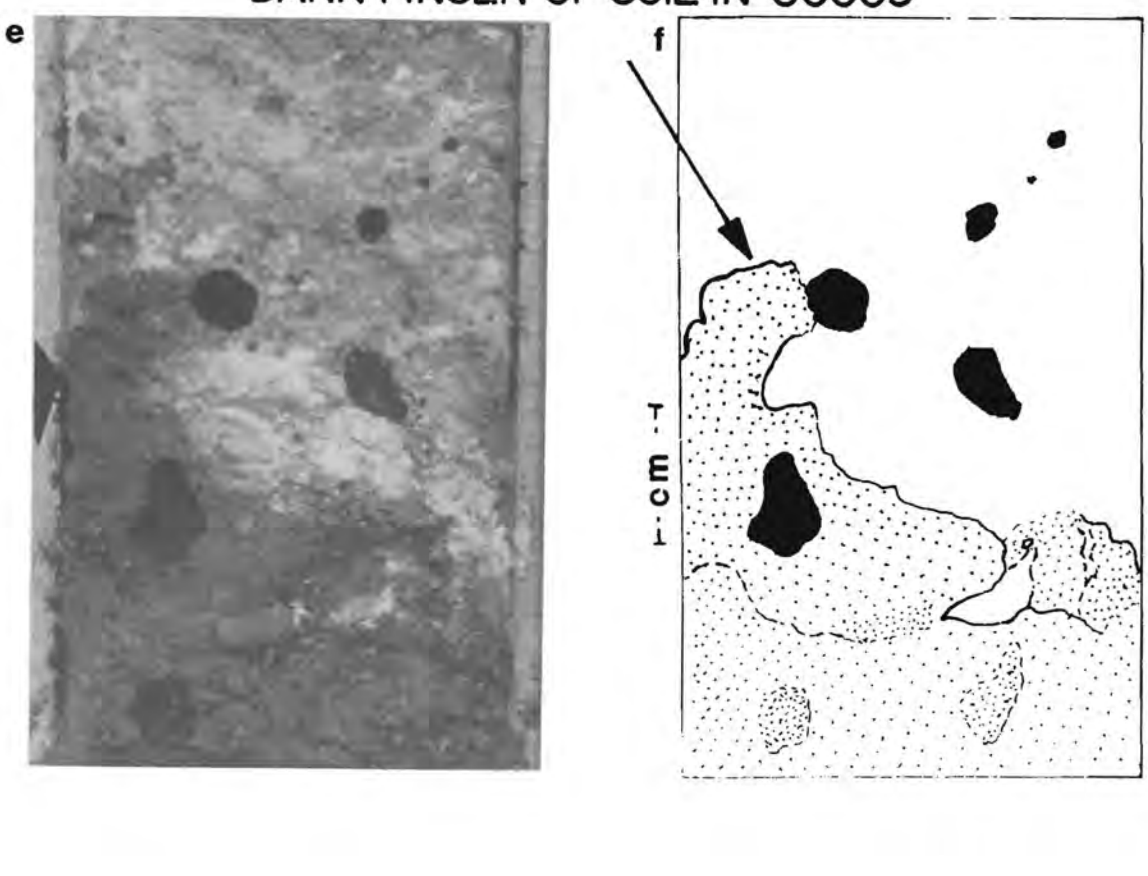
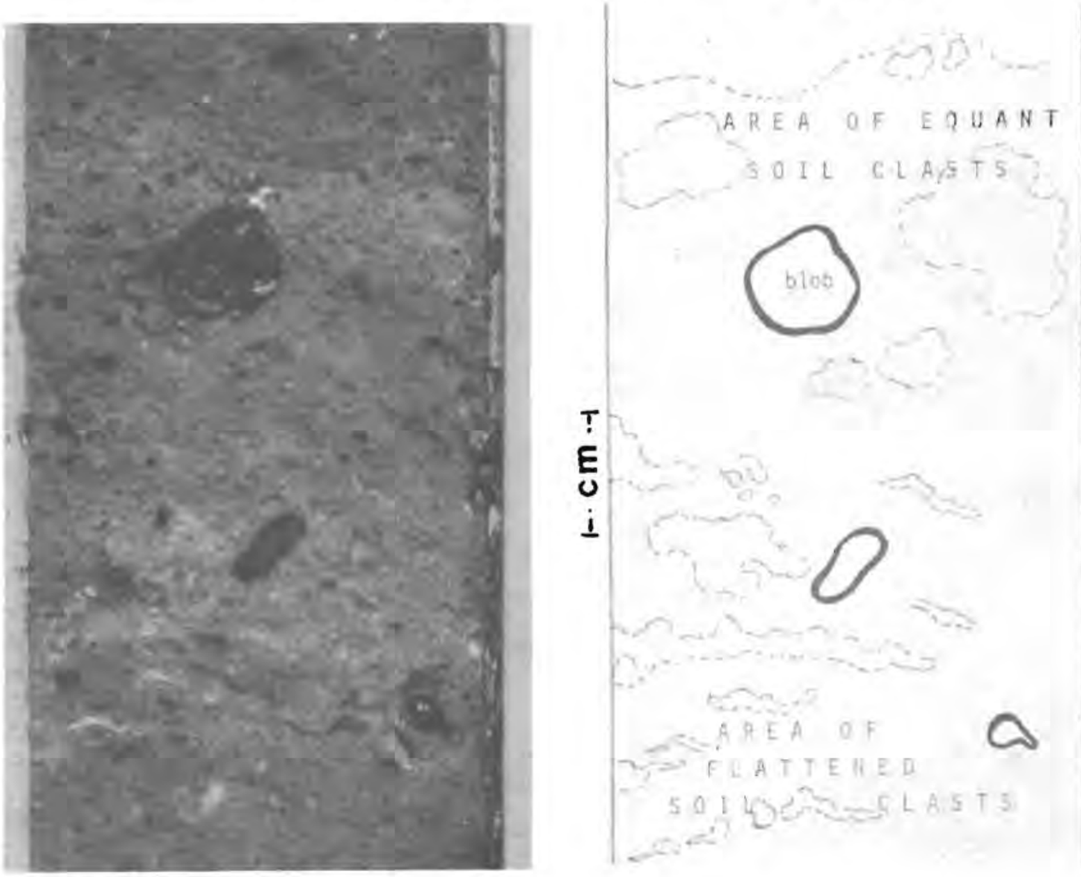


Fig 3 CLAST SUCCESSION IN 60009



being flattened. In some marbled units in 15008 and 60009, some clasts are coated with glass; one is illustrated in Nagle (1981).

If soil breccias are unmodified lithified soil, $\sim$30% should show features similar to marbled soils; none do. The only internal structure of soils which is also seen in breccias is the radial-arcuate clump. In some breccias such as lunar breccia 10061 or the Bununu meteorite, clumps are coiled in only one direction, analogous to lunar soils. In other rocks, such as breccia 15459 or meteorite EETA 79002, radial arcuate features show reverse twists in the vicinity of rock fragments; the curvature and spiral-like alignment of rock fragments is reminiscent of curvature seen in the wake of a boat. Differences between breccias and soils suggest the idea that the breccias have been modified during lithification, and may not be fully representative of parent soils.

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H5 CLAST AND UNEQUILIBRATED HOST IN YAMATO 75028 CHONDRITE BRECCIA. Tsutomu Ohta and Hiroshi Takeda, Mineralogical Institute, Faculty of Science, University of Tokyo, Hongo, Tokyo 113, Japan

The nature and origin of lunar breccias have given us better understanding of the meteoritic breccias. LL-group chondrites are well known for their brecciated texture and foreign clasts. Wilkening (1977) pointed out evidence for mixing among asteroids based on her observation on meteoritic breccias. Foreign materials called xenoliths or clasts have been found thus far within host meteorites representing eight meteorite classes (Anders, 1978). Most of the xenoliths are carbonaceous chondrites; ordinary chondrites and their relatives are the second most abundant class. Very recently Graham (1981) reported an unequilibrated inclusion in the Romeo (H4) chondrite. A variety of clasts, including H4 and H5 chondrites and other chondrite groups, in the Dimmitt H chondrite was examined by Rubin et al. (1981).

Yamato 75028 meteorite was first classified as an H 3 chondrite on the basis of the olivine and pyroxene compositions (Yanai et al., 1978). Subsequently Takeda et al. (1979) identified equilibrated H-type clasts in the host which showed unequilibrated texture. In the present study we have examined a few more new thin sections of Yamato 75028 chondrite and report the interim results of petrology and chemistry of the chondrite.

Yamato 75028 is a very weathered 6.1kg chondrite. Brown limonitic staining pervades all the prepared thin sections. Dull black fusion crust covers one thirds of the stone. Regmaglypts are seen on one surface. Many fractures penetrate into the stone. The interior exposed by chipping along a pre-existing crack is extensively weathered. However the sawed surface appears to be less weatherd than the chipped surface.

A small chip weighing 1.18g was supplied for bulk chemical analyses and for polished thin sections. The bulk chemical analysis yielded SiO_2 36.62, TiO_2 0.16, Al_2O_3 2.14, FeO 17.43, MnO 0.30, MgO 23.92, CaO 1.72, Na_2O 0.85, K_2O 0.10, $H_2O(-)$ 0.13, $H_2O(+)$ 0.4 (including volatile compositions), P_2O_5 0.37, FeS 3.02, Fe 10.80, Ni 1.00, NiO 0.69, Co 0.034, and Cr_2O_3 0.57 wt%, total=100.25 wt% (Analysis by H. Haramura). Based on the differences in the overall abundance (Fe/Si) and state of oxidation (Fe metal /total Fe) of Fe in the chondrite, the chondrite chemical group is between H and L, around Tieschetz H3 chondrite, though the SiO_2 content plotted against the MgO lies in the region for the H chondrite group.

Microprobe analyses show variable compositions for both olivine and pyroxene, but a prominent peak was observed within the known range of iron concentration of equilibrated H chondrites. One of the thin sections consists of clasts of higher petrologic grade (H5-6) and the matrix portion with distinct spherical chondrules. Microprobe analyses of the largest clast 5.5x2.9 mm in size show olivine and pyroxene to have essentially uniform composition comparable to the equilibrated H chondrites.

Another thin section was prepared from the chip near surface of the meteorite. Chondritic structure is readily delineated, including porphyritic chondrules, but the margins of the chondrules tend to merge with the granular groundmass which consists of olivine, pyroxene, nickel-iron and troilite. Some relatively large angular crystal grains are observed in the matrix. This part of the sample appears to consist of H5 material.

Reexamination of a sawed surface of the meteorite revealed that brownish gray clasts up to 5x2 cm in dimension were embeded in the dark gray host material (Fig. 1). The other two sections were made from the chips with the subnumbers 75028,62 and 75028,77 (Fig. 1). The chemical group of these two sections were visually estimated but not conclusive. The section 75028,62 is probably of group H; the section 75028,77 is of group H or L. Chondritic structure is well developed in both of the sections, though the margins of some of the chondrules tend to merge with the matrix. Various types of chondrules have been observed, including porphyritic, microporphyritic, granular and radial chondrules. Polysynthetically twinned clinopyroxenes are also observed. Some of the silicate grains show undulose extinction. A lot of chondrules are fragmented. Black glassy veinlets cross some of the chondrules. Many of the porphyritic chondrules are deformed and ellipsoidal. A clast 1.5x2 mm in size was found in one of the sections. The clast is similar to the H5-like clast found in another section described previously. Small clast-like parts are also found but they seem to be deformed porphyritic chondrules rather than rounded fragments of clasts. On the other hand, a few small portions of the thin sections show somewhat recrystallized textures.

The bulk chemistry of Yamato 75028 is intermediate between those of H and L groups but is similar to that of Tieshetz H3 chondrite. The host is most likely H3 material but one can not exclude the possibility that the host is the L or LL material. The textures are not indicative of the brecciated LL matrix. Fragments of H5 clasts were seen in the host material within the thin sections examined. A plausible interpretation of this chondrite is a low metallic and sulfide iron H chondrite which is a genomict breccia consisting of the admixture of H3 chondrite with H5 clasts. The characteristics of the olivine and pyroxene compositions for H5 clast and H(L)3-like host resemble those for the H chondrites with light/dark structures studied by McSween and Lipschutz (1980). A part of the thin sections of Yamato 75028 is similar to that Bremervörde H3 chondrite which shows well developed chondritic textures with an indurated xenolith of type 5 material (Wasson, 1974). If a chondrite parent body has a type 6 core and type 3 crust and type 4 and 5 intermediate layers between them (Anders, 1978), one might expect brecciated regolith chondrite of mixtures of various petrologic types, by analogy of a howardite parent body (Takeda, 1979), though the H4 component seems to be not well represented in Yamato 75028. If there is an individual parent body for different petrologic types, the chondritic breccia could be created by a soft collision of small H5 and H(L)3 parent bodies.

Further studies such as volatile trace element analyses are required for a definite conclusion. In order to resolve the detailed textural relationship between clasts and host, a preparation of sawed slice will be preferred. The detailed study of this sort of breccias contributes significantly to the understanding of the impact processes on small bodies in comparison with the impact of small projectiles into a large body such as the moon.

We thank National Institute of Polar Research for the meteorite sample. We are indebted to Drs. G. Sato, H. Kojima, and K. Yanai for sample processing, and Dr. Y. Ikeda for discussion and Prof. Y. Takeuchi for interest in our work.

YAMATO 75028 CHONDRITE BRECCIA

Ohta, T. and Takeda, H.

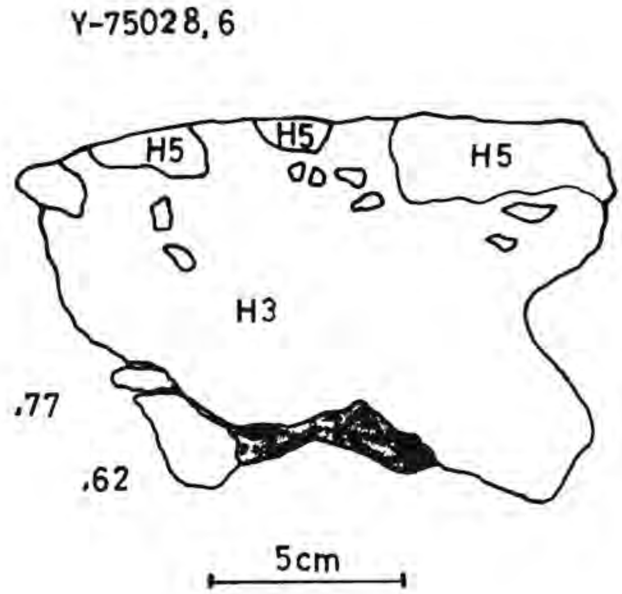

Fig. 1. Sketch showing the presence of H5 clasts observed on a sawed surface of Y-75028.

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CARBONACEOUS CHONDRITES: DO WE SEE RELICS OF PLANETESIMAL FORMATION IN THEM?

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In this paper we critically examine the unusual irradiation history of carbonaceous chondrites (1, 2) and what it means about the irradiation environment (1, 2, 3, 4, 5, 6). Specifically, it has been suggested that the irradiation occurred during the formation of Goldreich-Ward type planetesimals (4, 7) rather than in a regolith or megaregolith (8, 9, 10, 11, 12, 13, 14, 15, 16).

We will examine the status of 'compaction ages' in carbonaceous chondrites and try to deduce constraints on when the irradiation might have occurred, duration of irradiation and the time of final brecciation (17, 5, 18). Implications of all these results to the suggested model (4) will be discussed in detail.

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PETROLOGIC INSIGHTS INTO THE FRAGMENTATION HISTORY OF ASTEROIDS.

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Theoretical studies of the collisional evolution of asteroids (Davis and Chapman, 1977; Davis et al., 1979; Hartmann, 1979; Housen et al., 1979) indicate that for a large range in impact energies, collisions can disrupt asteroids but not impart sufficient velocities to most of the fragments to cause permanent dispersal. Under these conditions, gravitational forces cause most of the debris to reassemble, forming a brecciated rubble pile (Fig. 1). We present metallographic cooling-rate data for meteorite breccias that appear to require such a nondispersive fragmentation of chondrite parent bodies (which we presume to be asteroids).

The cooling rates of chondritic meteorites in the temperature range 800-600 K can be determined by plotting the compositions and sizes of compositionally-zoned taenite grains, and fitting the data to theoretically calculated cooling-rate curves (Wood, 1967; Willis and Goldstein, 1981a). Although the revised cooling-rate curves calculated by Willis and Goldstein (1981a) are accurate to within a factor of $\sim$2, analytical uncertainties and the effect of irregular grain geometry cause the actual uncertainties to be perhaps a factor of three. Cooling rates of equilibrated, unbrecciated chondrites agree with those determined by Pellas and Storzer (1981) by a totally independent method based on fission-track-densities and the differential annealing properties of minerals. Concerns that metallographic cooling rates may be in error by orders of magnitude due to initial compositional zonation in metal grains (Bevan and Axon, 1980; Hutchison et al., 1980) are completely unfounded (Willis and Goldstein, 1981b).

The H chondrite regolith breccias Weston, Fayetteville, Dimmitt, Plainview, Breitscheid and Tysnes Island have compositionally-zoned taenite grains in their clastic matrices that correspond to cooling rates of between $\sim$1 and 1000^{o}C/Myr (Scott and Rajan, 1981; Rubin et al., 1981; and our unpublished data) (e.g., Fig. 2). This wide range in cooling rates implies a similarly wide range in original burial depths. Using Wood's (1967) thermal models, we find that the more slowly-cooled (1-20^{o}C/Myr) materials composing regolith breccias were derived from depths of $\gtrsim$40 km on bodies $\gtrsim$100 km in radius. The most slowly-cooled (1^{o}C/Myr) grains could have been derived from depths as great as 100 km on asteroids 200 km in radius and the most rapidly cooled ($\sim$1000^{o}C/Myr) grains from depths of only a few kilometers. The greatest uncertainties in these depth estimates arise from the parameters in the thermal model, not from uncertainties in the measured cooling rates. For example, if the thermal diffusivity was actually substantially smaller than the 0.007 cm^2/sec value used by Wood (1967), then the depths would be correspondingly shallower. A diffusivity 100 times smaller than Wood's (1967) estimate (thus, comparable to that of the lunar regolith: $\sim$10^{-4} cm^2/sec; Langseth et al., 1976) corresponds to burial depths that are ten times shallower than those determined by Wood (1967). However, it is improbable that the diffusivity would be so small throughout an asteroidal-sized object, even if the object contained some unconsolidated materials (Scott and Taylor, this volume).

Thus, the most slowly cooled taenites in the clastic matrices of the regolith breccias must have been derived from tens of kilometers depth. How could such material be brought to the surface? An obvious mechanism would be excavation by impact; this can be ruled out, however, because impacts sufficiently energetic to excavate material from >40 km would disrupt asteroids smaller than ∿400 km in diameter. For example, employing the approach used by Housen et al. (1979) (which is based on work by Gault and Wedekind, 1977), we estimate that the largest crater that could form on a 300 km diameter, rheologically "strong" asteroid is ∿150 km in diameter. Gault and Wedekind (1977) found that the depth/diameter ratios of impact craters are essentially independent of planetary surface gravity. This was confirmed by the observations of Malin and Dzurisin (1977, 1978) that showed that crater depth/diameter ratios of the Moon and Mercury are the same within 10%. We thus can use the depth/diameter ratio of 0.2, appropriate for fresh lunar craters ≤15 km in diameter (Pike, 1977), to determine the depth of the "largest possible crater" on a 300 km diameter strong asteroid. This 150 km diameter crater would be only about 30 km deep, less than the required minimum depth of 40 km. Furthermore, the material actually ejected beyond the crater rim would be derived from even shallower depths (the upper third of the crater) (Stöffler et al., 1975). Because of compression of the target material, even the rock exposed on the floor of the crater would have originated above the nominal 30 km crater depth.

If single cratering events cannot deliver the needed material to the surface of a chondrite parent body, perhaps numerous smaller events can, by gradually eroding an asteroid until the appropriate depths are exposed. Such a mechanism could certainly operate to expose progressively deeper levels in a body, but it does not account for the coexistence in the regolith of materials derived from a wide range of depths (as is represented by the wide range in cooling rates of taenite grains in the chondrite regolith breccias).

Another possibility is that the parent body was disrupted and dispersed, so that the largest fragments contained (on or near their surface) material that had cooled at a variety of depths (5-40 km) in the original parent body. However, this is an improbable occurrence because there is a sharp transition from impact energies low enough to form craters (without parent body disruption to those large enough to disrupt the target and fragment it into relatively small pieces (Hartmann, 1978; Fujiwara et al., 1977; Greenberg et al., 1978). For example, using a relation given by Fujiwara et al. (1977), we calculate that the energy density required to break up an object, such that the largest fragment contains between 20 and 60% of the original mass, ranges from 0.6 to 1.5×10^7 ergs/g. For collisions between 50 km and 200 km diameter bodies, this energy range corresponds to a narrow impact velocity range: ∿0.3 - 0.5 km/sec.

We are thus left with a model that requires chondrite parent bodies to have been disrupted and subsequently reassembled. This process would lead to a chaotic pile of debris with a surface regolith containing material derived from a variety of depths. Reworking and compaction of this regolith would produce a rock with the characteristics of chondrite regolith breccias, including the presence of compositionally-zoned taenite grains that record a wide range of cooling rates.

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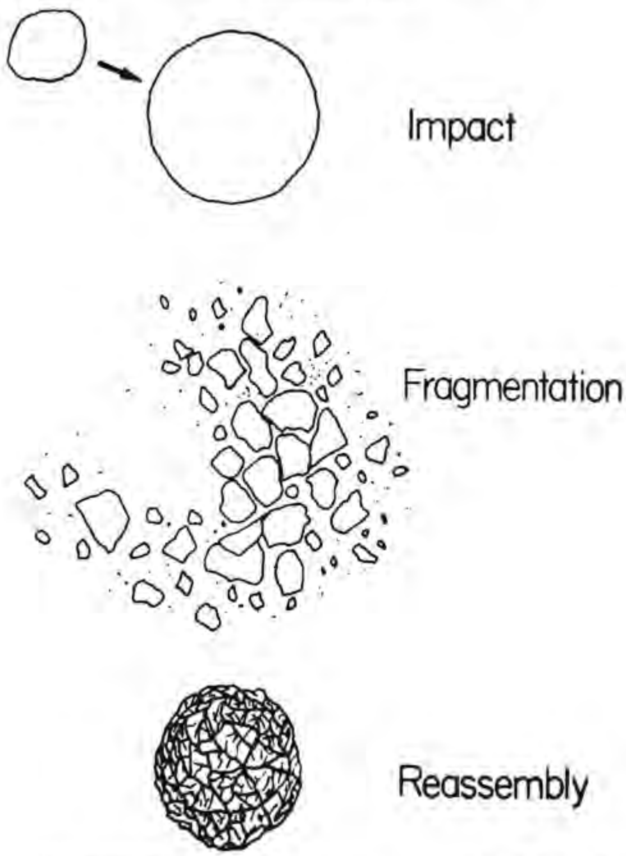

Fig. 1. After an energetic impact, many large asteroids may have been catastrophically fragmented, with subsequent reassembly of most of the pieces.

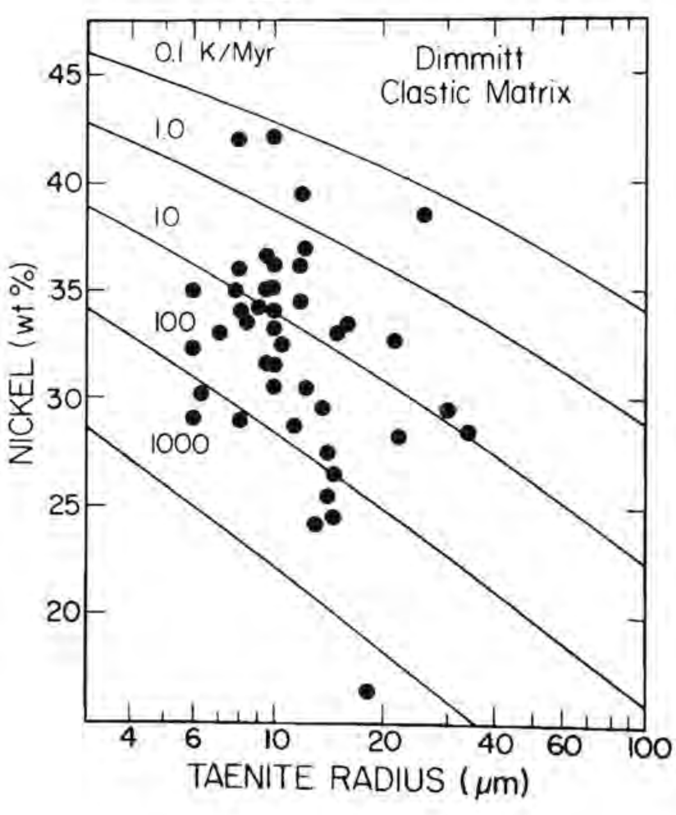

Fig. 2. Metallographic cooling rates of compositionally-zoned taenites in the clastic matrix of the Dimmitt H chondrite regolith breccia.

NUTSHELL GUIDE TO LUNAR BRECCIAS. Graham Ryder, Lunar Curatorial Laboratory, Northrop Services, Inc., P.O. Box 34416, Houston, Texas 77034

IMPACTS AND BRECCIAS

Meteoritic impacts have had a strong influence on lunar topography, producing craters of all sizes up to hundreds of kilometers. The inference that the fragmental rocks and soils which dominate the lunar samples were generated in impacts is substantiated by the shock features present in many samples, and by the meteoritic contamination (Ir, Au, etc.) of the soils and many rocks which is lacking in the endogenic igneous rocks such as mare basalts. The normal definition of the word breccia has generally been extended to include glasses and igneous and metamorphic rocks which contain no clasts, if there is compelling reason to believe that they were impact-generated.

The main purpose of this abstract is to summarize lunar breccias, with the exception of regolith breccias. (In general, regolith breccias are deemed to be those containing components created or normally embedded in the upper few meters of the Moon, e.g., impact-produced glasses, agglutinates, and solar wind components.) In this abstract, lunar breccias will be described using the classification system of Stöffler et al., (1980) for highland rocks (Table 1). It is easily extendable to include mare breccias, although almost all breccias produced on mare surfaces are regolith breccias.

TYPES OF LUNAR BRECCIA

Lunar breccias comprise a variety of textural types and chemical compositions, and their complexity is demonstrated in general reviews by James (1977), Phinney et al., (1977), Simonds et al., (1974), Stöffler et al., (1979, 1980), and McGee et al., (1979). Many of the large breccias have been studied in detail while many of the smaller ones have hardly been studied at all. Samples were chipped from boulders and picked or raked from regolith. They range from friable to tough; from vitric to crystalline; and from fragment-rich to fragment-poor. Similar samples have been given different names under varied classifications and descriptions, making literature comparisons difficult; Stöffler et al., (1980; Table 5) list many of the synonyms and references for them.

Lunar breccias are too complex to be classified meaningfully on any single characteristic unless the classification is intended for a very specific purpose. Stöffler et al., (1980) emphasize the textural characteristics of the clast-matrix relationships of the entire sample (first-order) (Table 1). Chemical and mineralogical characteristics are used as modifying terms (second-order). However, the textural characteristics of lunar breccias do correlate to some extent with composition. In many cases, the matrix is an entity distinct from the fragments, e.g., melt rocks; but in other cases, the rock is merely a seriate size assemblage of clasts, and the distinction of matrix and clasts is arbitrary, e.g., friable fragmental rocks. For a more complete rationale for the classification and its nomenclature, which is influenced by studies of terrestrial impact breccias, see Stoffler et al., (1980).

Monomict Rocks:

Cataclastic rocks consist of a single crystalline lithology which has been crushed or brecciated more or less in situ. Many do not have meteoritic contamination and are merely crushed plutonic rocks, including anorthosites from the Apollo 16 site and the dunite. However, some crystalline impact melt and metamorphic rocks have also been crushed, and although the original lithology was polymict, the present rocks consist of fragments which are all the same.

Metamorphic cataclastic rocks are those cataclastic rocks for which there

TABLE 1. Classification of Lunar Breccias Group (from Stöffler et al., 1980)

Subgroups	Classes (Root Names)	Main Textural Characteristics	Examples
Monomict or monolithologic	Cataclastic rock	Intergranular in-situ brecciation of a single lithology	60025, 65015, 72415
	Metamorphic (re-crystallized) Cataclastic rock	Intergranular in-situ brecciation of a single lithology and partial recrystallization	67955?
Dimict or dilithologic	Dimict breccia	Intrusive-like, veined texture of very fine-grained crystallized melt breccia within coarse-grained plutonic or metamorphic rock types	61015, 62255, 64475
Polymict or polylithologic	Regolith breccia or soil breccia	Clastic regolith constituents including glass spherules with brown vesiculated matrix glass	10018, 14313, 15205
	Fragmental breccia	Rock clasts in a porous clastic matrix of fine-grained rock debris (mineral clasts)	14063, 14082, 67115, 67455
	(Crystalline) melt breccia or impact melt breccia	Rock and mineral clasts in an igneous-textured matrix (granular, ophitic, subophitic, porphyritic, poikilitic, dendritic, fibrous, sheaf-like, etc.)	14310, 14312, 15455, 62235, 62295, 68415
	(Impact) glass or glassy melt breccia	Rock and mineral clasts in a coherent glassy or partially devitrified matrix	60095; glass coats
	Granulitic breccia	Rock and mineral clasts in a granoblastic to poikiloblastic matrix	67955?, 77017, 79215

is evidence of a subsequent metamorphism, usually a recrystallization of the finer matrix.

Dimict Rocks:

Dimict breccias (James 1981; Warner et al., 1973) comprise two lithologies which are distinct: one is coarse-grained, light-colored, and usually anorthosite; the other is fine-grained, dark-colored, and an impact melt. The rocks have a dike-like structure, but in almost all examples the lithologies are mutually intrusive or at least fragmented, and in some samples the relationships are quite complex. The dimict breccias are most common among Apollo 16 samples, especially those from the southern part of the site. The older term "black and white breccias" is not quite synonymous, because it has been widely used to describe two Apollo 15 samples, 15445 and 15455, in which the white material is not a single lithology; their dark material is not fragmented but a single homogenous mass in which the white materials are clasts.

Polymict Rocks:

Fragmental breccias (formerly light matrix breccias) (James 1981; Minkin et al., 1977; Norman 1981) are an assemblage of dominantly angular mineral and lithic fragments, barely bonded by glass or melt (Phinney et al., 1977). Most are porous and friable, and some have disintegrated because of their friability. The fragment size distribution is seriate. Most of the samples are very feldspathic, hence pale-colored. They are particularly common among samples from the North Ray crater area of the Apollo 16 site, but a few were collected at the Apollo 14 site. Stoffler et al., (1980) distinguish two types according to whether or not they contain cogenetic melt particles; such a distinction requires a detailed knowledge of a rock, and has not yet positively been made for any sample.

Crystalline melt breccias, or impact melt breccias (Simonds et al., 1974; Vaniman and Papike 1980) have an igneous-textured crystalline matrix containing rock and mineral clasts. The matrix textures range from fine-grained to coarse-grained, and include poikilitic, subophitic, and more rarely porphyritic textures. Most such rocks are quite homogeneous, but some fine-grained, schlieren-bearing samples are heterogeneous (72215, 73255). The subophitic rocks tend to contain fewer clasts and to be more aluminous than poikilitic samples. However, the most aluminous samples are extremely fine-grained, clast-rich, and dark-colored; these are common as clasts in fragmental breccias.

Impact glass and glassy melt breccias are surely self-explanatory terms. Glass is common as a coating on rocks. Glassy breccias are commonly heterogeneous.

Granulitic breccias (Warner et al., 1977; Stewart 1975) contain mineral and rock clasts or relics which survived the recrystallization of the matrix in a recognizable form, although the clasts, too, are recrystallized. The matrix is poikiloblastic or granoblastic, and in the granoblastic rocks 120° triple junctions are common. (Stoffler et al., (1980) distinguish clast-free varieties as metamorphic rocks, not breccias at all, but the distinction is not objective in many cases.) Nearly all these samples contain about 70 or 75% plagioclase and have equilibrated mineral compositions. The granulitic breccias are common as clasts in other breccias at all Apollo highlands landing sites, and many of the "anorthosite" fragments noted in the Apollo 11 soils (Wood et al., 1970) are granulitic breccias.

BRECCIAS, CRATERING, AND TARGETS

There are two aspects to the study of breccias: formation and provenance. The study of breccia formation is to understand how and when an impact assembled and subsequently lithified a rock. These studies contribute to unravelling the bombardment history as well as to the details of rock formation. The study of provenance is to understand the target area. There has been a strong desire to interpret through all the impact events affecting a rock to identify the characteristics of the magmatic rocks which contributed to its mineralogy and chemistry. Breccia formation and provenance interpretations are interrelated, because formation can bias mineral and lithic clast populations and can be influenced by the types of material which constitute the target.

An impact produces a range of shock pressures and ensuing breccia textures, as observed at terrestrial craters, where rock characteristics and field control allow reasonable interpretations of relationships and processes. The characteristics of a breccia depend on the size of the impact, the target material(s), and its relationship with the crater, e.g., whether ejecta or subfloor. The study of terrestrial craters has been important for understanding lunar breccias (Simonds et al., 1976; Stoffler et al., 1974, 1979). However, on the Moon individual samples can rarely be confidently assigned to specific craters, as there is almost no field control. The formation conditions of lunar breccias differ from those of terrestrial ones in several respects: lunar cratering occurs in volatile-poor rocks and in targets subjected to previous cratering events. The target includes breccias, and this can result in multigenerational breccia-in-breccia textures; however, similar textures occur in terrestrial breccias produced in single events. Breccias produced on asteroids are expected to have characteristics and problems of interpretation more like those of lunar breccias than those of terrestrial breccias.

Breccia Formation:

Concepts of the formation of lunar breccias changed vastly as different types of breccia were sampled; as they were studied in greater detail; as regional geological interpretations changed; and as information from terrestrial, experimental, and theoretical cratering studies became available. Shock lithification (Christie et al., 1973; Kieffer 1975) and metamorphism (Warner 1972; Williams 1972) have been invoked and are still relevant for some cases, but, in general, impact-lithified rocks are acceptably explained to result from geologically rapid heating and cooling. This model has been advocated and refined by Simonds (1975) and Simonds et al., (1976): Near the point of impact superheated silicate melt is produced and mixes rapidly to a millimeter scale with cooler, unshocked fragmental debris as it moves outwards. The mixture rapidly reaches thermal equilibrium, and some low-melting-point clasts are digested. The matrix crystallizes and heat is lost to the surroundings. The final characteristics of the rock depend on the temperature at which clast-melt equilibration is reached: generally, the fewer the clasts, the higher the temperature. With very little melt, glass is formed (e.g., fragmental breccias); with abundant melt, well-developed igneous textures (e.g., subophitic impact melts) develop. This is summarized in Figure 1. The clast content and cooling of the melt have a significant influence on the resulting texture of the crystallized rock (Ryder and Bower 1976; Lofgren 1977; Thornber and Huebner 1980). In most cases, then, the assemblage and lithification occur in the same event; granulitic breccias and any rocks lithified by shock alone (some regolith breccias?) presumably require separate assembly and lithification events. For granulitic rocks the heat might not be of impact origin.

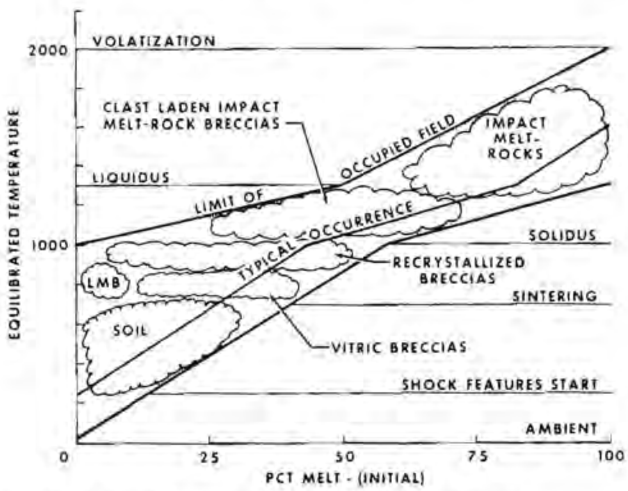

Figure 1. from Simonds et al., (1976)

Breccia Compositions and Provenance:

The provenance of a breccia can be deduced from its bulk chemistry and from its clast population. Several studies using least squares mixing models have attempted to understand what the components are (e.g., Boynton et al., 1976; Schonfeld 1974; Wasson et al., 1977). On composition plots (e.g., Figure 2) the breccias fall between pristine (igneous) rocks and have a narrower compositional range, suggesting that they are fairly simple mixtures. However, breccias cannot be precisely modeled from known pristine components (see Ryder 1979). In detail they also contain a meteoritic component, and the volatile elements do not adhere to any simple mixing rules. Samples near the center of the range roughly contain more Ni (Figure 2), which is mainly from meteoritic contamination, and they may be more mixed than other samples.

Lithic clasts provide an indicator of the provenance, but for impact melts there appear to be some problems. The bulk compositions of impact melts (e.g., the Apollo 17 boulders) cannot be derived from their lithic clast content, unlike terrestrial impact melts. They always contain a cryptic KREEP component, much too abundant to be accountable by clast digestion, even though the mineral clast population is more refractory than the bulk rock. The cause is unknown but suggests that the melted part of the

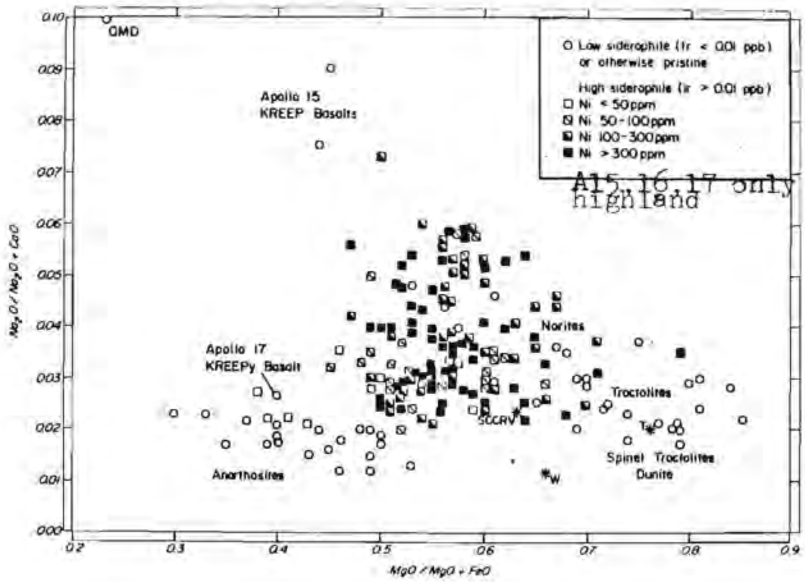

Figure 2. from Ryder (1979)

target is distinct from the cooler, unshocked ejecta. This might be reasonable for basin-sized impacts. The use of mineral clasts to provide provenance indications is not at present very refined, but with accurate trace element analyses of breccia mineral clasts and of the minerals in pristine rocks, it could be a very useful method.

The compositions and textures of breccias are not entirely independent. Nearly all breccias contain a KREEP component (especially abundant at the Apollo 14 site), but granulitic breccias do not, and indeed have very low rare earth contents. Fragmental breccias (feldspathic) do contain a KREEP component, but not much. Most poikilitic impact melts have high KREEP contents and approximately 18% Al_2O_3 (approximately cotectic); subophitic impact melts have lower KREEP and higher Al_2O_3 abundances (20-25%).

Breccia Ages:

Breccia formation is a violent, disequilibrium process, and severe thermal effects, not shock alone (e.g., Ostertag 1981), are required to bring about enough degassing or re-equilibration to allow a definable isotopic age to be determined. Most rocks have not been sufficiently heated to reset Rb-Sr or Sm-Nd clocks, and for this reason, as well as the prevalent fine grain-sizes, few mineral isochrons have been presented. Most lunar breccia ages are Ar-Ar, and these are complicated by clasts. For those for which a good plateau has been obtained, ages of 3.9-4.0 billion years are by far the most common (Maurer *et al*., 1978), and a few ages up to 4.2 billion years are possibly reliable. In general, the oldest breccias are monomict or granulitic; crystalline impact melts are 3.9-4.0 billion years; and from stratigraphic considerations, regolith breccias and glasses are the youngest (less than 3.9 billion years). The formation of some breccias, the feldspathic fragmental rocks for instance, has not been dated at all.

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ELECTRON MICROPROBE STUDY OF IMPACT-MELTED REGOLITH BRECCIAS

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Of processed samples among about 3,000 Yamato-79 meteorites, there were found large lithic materials of LL-group chondrites.
Dark colored stones have a very fine-grained glassy texture and full of vesicles and contain both light-colored and black inclusion in hand specimen. The bulk chemical composition of Yamato-790964 of this type (analysis by H. Haramura) indicates it is LL-group chondrite. The microscopic examination of polished thin sections and the electron microprobe analyses of selected specimens revealed that these meteorites are similar to some lithic fragments known in LL-group chondrites described by Fodor and Keil (1978). They can be classified owing to degree of shock-melted recrystallization. Brief petrographic descriptions of 3 specimens (Yamato -790143, -790345, -790964) are given in sequence from low-grade recrystallization to high-grade.

(1) Yamato-790345 (236.6g) is finely brecciated, shock-compacted LL-chondrite. The fragments of chondrule can be recognized, but the margins of chondrule are indistinct and tend to merge with the comminuted matrix, consisting largely of olivine and pyroxene. Shock veins are observed, but a shock-melted matrix is not obvious and a few vesicles are seen.
This specimen can be classified as heavily shocked LL-chondritic materials on the basis of the pyroxene and olivine compositions.

(2) Yamato-790964 (3335g) shows very fine-grained crystalline texture. The interior is very porous, with elongated channels in irregular orientation. Chondrule outline and margin are indistinct, tending to merge with a matrix. But some chondrule structures are visible, and chondrule types include barred olivine and fine-grained pyroxene. The largest chondrule still visible in the polished thin section (total area about $2cm^2$) has a maximun diameter of approximately 2mm. In a matrix, small amount of brown glass and fine-grained glassy materials fill interstices of lath of euhedral pyroxene crystals and fragments of minerals, including coarse remnant olivines. Most of larger olivine and pyroxene grains show undulating extinction. Numerous closely spaced fractures in some mineral grains are also apparent. Margins of these minerals are fractured into fragments and integrated with glass. Euhedral pyroxene crystals embeded in an extremely comminuted and vitreous matrix, usually show chemical zorning, that is Ca-enrichment at the rim (Fig. 2). Slight enrichment of Al-content toward the rim is also observed (0.68 wt.% at the core, 1.82 wt.% at the rim). They may have been formed by rapid crystallization from an impact melt. The presence of small euhedral olivine crystals with sub-micron in size scattered in the glass suggests that they also may have grown from the melt. Some olivine grains have high Fa-component, exceeding the LL-group range (Fig. 1). This specimen can be described as fine-crystalline chondritic materials.

(3) Yamato-790143 (52.3g) is full of irregular vesicles, occupying about 20% area in the polished thin section. The area of vesicles in Yamato-790143 is larger than in Yamato-790964. The shape of vesicles suggests that they were formed by vaporization of materials and squashed in a hot ejecta blanket. Chondrules are sparse and ill-defined. Only one fragment of chondrule is visible in the small area ($0.5cm^2$) of the polished thin section, which consists of polysynthetically twinned pyroxene and is approximately 1.0mm in diameter. Lath of euhedral pyroxenes and fine-grained fragments with composition of the LL-group are set in a shock-melted

dark matrix, which shows fine granoblastic texture with glass.
A area occupied by glass in Yamato-79143 is larger than Yamato-790964. Glass usually surrounds irregular vesicles in Yamato-790143, but in Yamato-790964, vesicles are distributed in direct contact with minerals. Some olivene fragments show undulatory extinction and may be relict. This specimen can be classified as vesicular glassy chondritic materials formed from a shock-melt.

The three types mentioned above are genetically related each other and even transitional. These textures are often recognized within one meteorite such as Yamato-790964.
These meteorites are large samples of lithic fragments common in the brecciated LL-chondrites, and are interpreted as suface regolith materials of the LL-parent body that were subjected to various degree of shock melting, crystallization from a melt, shock recrystallization, and brecciation due to intense impacts and eventually consolidated into coherent rock. The mechanism has been postulated in comparison with vesicular glassy breccia found in lunar samples. Yamato-790964 has a similar feature to lunar vesicular breccia, 60017. The large amounts of these meteorites will significantly contribute to reconstract the LL-chondrite parent body and the shock process on the surface, and also to better understanding of the lunar analogues.

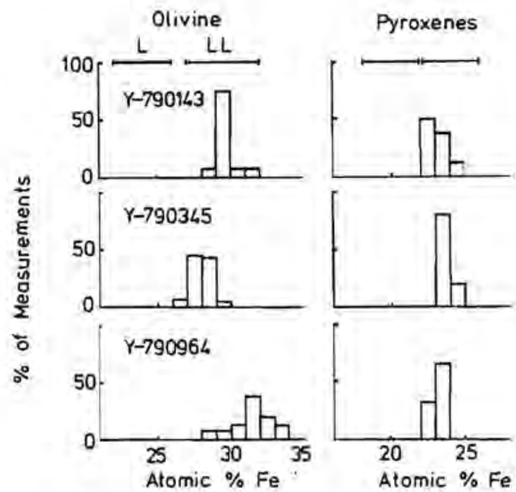

Fig. 1 Histogram showing iron contents of olivine and low-Ca pyroxene in three specimens. The compositional ranges are from Keil and Fredriksson (1964).

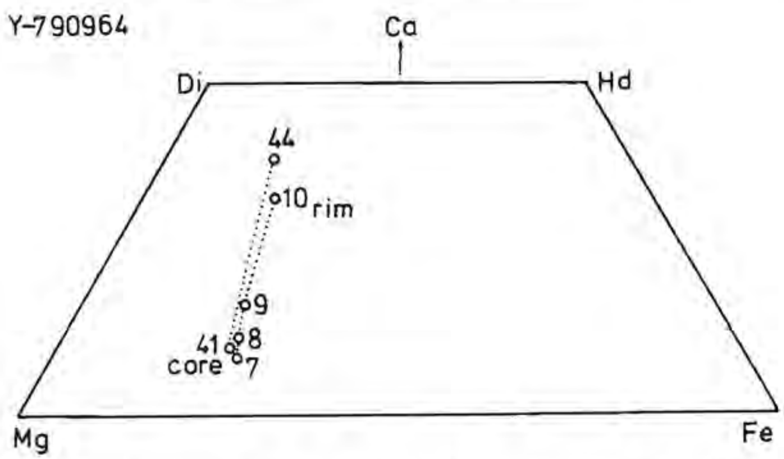

Fig. 2 Composition of euhedral pyroxenes in Yamato -790964. Dotted lines indicate the continuous zorning within single crystal. Ca-enrichment at the rim is shown.

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Fig. 3 Photomicrograph of Yamato-790964. Euhedral pyroxene crystals are embeded in an extremely comminuted mineral fragments and brown-colored glass. These pyroxenes show Ca-enrichment at the rim. Width:0.8mm

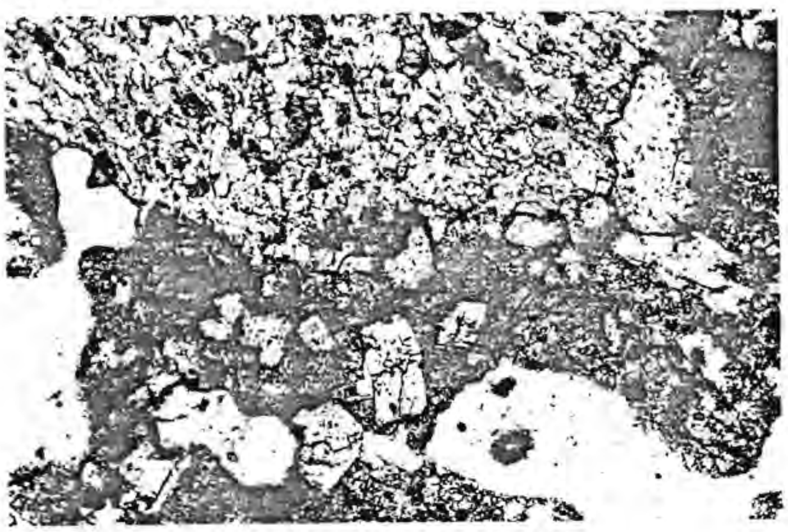

Fig. 4 Photomicrograph of Yamato-790143. In the upper part, poorly defined chondrule is seen and merged with vitreous matrix. This specimen is full of irregular vesicles. Width:0.8mm

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AGES OF SERENITATIS BRECCIAS

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It has been pointed out by Müller et al. (1977) that the Apollo 17 highland breccias may not have been completely degassed. The range in $^{39}Ar-^{40}Ar$ plateau ages observed by various workers from 3.90 to 4.02 G.y. is not due to a range in the ages of the events producing the rocks but more likely a correlation to the amount of degassing. A suggestion was made that in fact the majority of the Apollo 17 breccias were all formed in the same major impact event approximately 3.90 G.y. ago. The most slowly cooled, gray-green breccias were most completely degassed, and the least slowly cooled, like the gray breccias, were least completely degassed. The ages of the stratigraphically highest, the light gray breccias, had been interpreted by Turner and Cadogan (1975) as very likely defining the time of the Serenitatis event at 4.02 G.y. ago. In order to check whether these breccias are really older than 3.90 G.y., we have used the laser microprobe to measure, in polished sections of 72215 and 72255, the ages of plagioclase clasts, high-K feldspar, and felsite clasts. The samples represent two rocks taken from Boulder 1 at Station 2, Apollo 17. The geologic setting has been described in detail by Wolfe (1975). The boulder is derived from the upper portion of the South Massif, at a location that is part of the third ring of the Southern Serenitatis basin. A number of the Serenitatis breccias are derived from the upper portion.

Ryder et al. (1975) have described the petrology of these samples extensively and conclude the boulder consists of two separate entities: 1) "a metamorphosed breccia containing a diverse lithic clast population, and 2) a friable matrix containing KREEPy basalts." Based on petrologic constraints, they attribute the two components to origins relating to two impact events, one characterized by high temperature and the other to a cooler temperature. The question that arises is whether it is possible to date these events and assign them to impact features on the lunar surface. Leich et al. (1975) have performed stepwise thermal release $^{39}Ar-^{40}Ar$ studies of samples 72255 and 72275. They obtained a plateau age of 3.99 ± 0.03 G.y. for a large norite clast also dated using Rb-Sr (Compston et al., 1975). The Rb-Sr age was 4.17 ± 0.04 G.y., assuming a closed system. The matrix next to the clast was also dated using $^{39}Ar-^{40}Ar$ and yielded a plateau age of 4.01 ± 0.03 G.y. Thus 4.00 ± 0.03 G.y. seems to mark the beginning of argon retention in sample 72255. Their studies of 72275 did not yield reliable plateaus, but the data were consistent with a 4.00 ± 0.03 G.y. age for that sample also.

We made a laser microprobe study of two samples from Boulder 1, Station 2, Apollo 17 (72215,144 and 72255,134). The results are shown in Table 1. A similar study was made for breccia 73215 (Müller et al., 1977). The age of the melt derived groundmass, 4.01 G.y. for 73215, was found to have no chronological significance. Instead the best estimate for the time of the breccia forming event, 3.90 G.y. ago, came from the study of K-rich felsic glass clasts. As can be seen in Table 1, the same situation exists for the samples from Boulder 1, Station 2, Apollo 17. The high-K clasts gave the youngest ages of 3.91 ± 0.03 G.y. While we did not make a complete study of the clasts, the plagioclase clasts studied had somewhat higher ages of 3.97 ± 0.06 G.y. Under the assumption that the high-K clast have well developed plateaus above 650°C, the laser ages which are total release, K-Ar ages, are reliable. We made two series of measurements: one in which the samples have not been preheated before lasering, and one in which the samples have been heated to 650°C after the neutron irradiation but before the release of the argon by laser melting. Most of the clasts are single-mineral grains of plagioclase that have K_2O contents ranging from < 0.05% to ∿ 0.20% (Table 1). Some of the analyzed plagioclase occurs within noritic lithic clasts. All plagioclase analyses give ages of ∿ 3.95 G.y. or greater. Felsite clasts consist of K-rich glass, K-feldspar, and silica, and these tend to give younger ages.

The K-rich clasts have been investigated by the ^{39}Ar-^{40}Ar method (Jessberger et al., 1977) which gave a plateau from 600° to 1200°C. Very little gas, with somewhat higher ages, was released above 1200°C. Thus there is circumstantial evidence that the laser ages are reliable.

The breccia age of the Boulder 1, Station 2, of the Apollo 17 was formed 3.90 G.y. ago, within error. The same is the accepted age for the Imbrium event. This would seem to indicate that perhaps a large number of lunar basins were formed in a relatively short time period. The only alternative would be that the breccias lying near the surface at the Apollo 17 landing site represent Imbrium ejecta.

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Table 1: Electron Microprobe Analyses of Selected Mineral Phases.

	72255,57		72255,134	72215,144	
Sample	K-feldspar	plagioclase	plagioclase	plagioclase	felsic glass
SiO_2	63.36	44.44	43.96	44.56	76.02
Al_2O_3	17.88	35.97	35.35	35.70	11.13
FeO	0.24	0.16	0.19	0.27	0.91
MgO	0.00	0.01	0.09	0.00	0.00
CaO	0.23	19.48	20.01	19.29	0.60
Na_2O	0.00	0.35	0.29	0.66	0.33
K_2O	16.46	0.08	0.05	0.16	9.33
Total	98.17	100.49	99.94	100.64	98.32

Table 2: Laser microprobe ages of individual minerals from Boulder 1 Station 2 Apollo 17

RN	Mineral	K%	Ca%	40/39	Age
		Sample 72255,134			
124	Plagioclase[1]	0.02	8	37.31 ± 0.33	3.973 ± 0.027
152	Plagioclase[1]	0.02	3.4	38.56 ± 1.73	4.026 ± 0.076
154	Plagioclase[1]	0.04	8	33.60 ± 1.28	3.806 ± 0.065
162	Plagioclase[1]	0.02	3.5	36.25 ± 1.73	3.927 ± 0.079
164	Plagioclase-Composite[1]	0.09	3.6	47.04 ± 0.62	4.349 ± 0.032
8072	Plagioclase-Composite[2]	0.30	<10	43.43 ± 0.99	4.220 ± 0.050
172	Plagioclase-Composite[1]	0.05	1.3	43.96 ± 1.00	4.238 ± 0.044
8102	Plagioclase-Composite[2]	0.04	<10	37.92 ± 1.42	3.980 ± 0.069
174	Plagioclase-Composite[1]	0.04	3	38.72 ± 0.61	4.032 ± 0.034
8104	Plagioclase-Composite[2]	0.04	<10	40.07 ± 10.00	4.140 ± 0.350
192	Plagioclase[1]	0.19	15	36.31 ± 0.50	3.929 ± 0.032
222	Plagioclase[1]	0.05	4	40.70 ± 1.52	4.113 ± 0.065
224	Plagioclase-Composite[1]	0.12	3	38.85 ± 0.31	4.038 ± 0.026
8184	Plagioclase-Composite[2]	0.16	<10	36.02 ± 1.24	3.968 ± 0.065
234	Plagioclase[1]	0.02	3	33.36 ± 0.73	3.794 ± 0.041
252	Matrix[1]	0.10	4	37.02 ± 0.35	3.960 ± 0.027
292	Matrix[1]	0.27	5	34.07 ± 0.19	3.828 ± 0.024
312	Matrix[1]	0.32	12	37.60 ± 0.32	3.985 ± 0.027
8112	Feldsparthoid[2]	3.9	<10	34.63 ± 0.57	3.901 ± 0.043
8132	Feldsparthoid[2]	2.3	<10	32.75 ± 2.75	3.820 ± 0.135
		Sample 72215,144			
8216	K-Feldspar[2]	3.1	2	35.85 ± 0.49	3.960 ± 0.040
9176	Plagioclase[1]	0.27	3	35.68 ± 0.72	3.902 ± 0.039
9181	Plagioclase[1]	1.2	6	36.82 ± 0.34	3.952 ± 0.027
9192	Plagioclase[1]	0.05	1	38.06 ± 0.88	4.005 ± 0.04[illegible]
9194	Plagioclase[1]	0.10	1	39.85 ± 0.91	4.079 ± 0.043
9202	Plagioclase[1]	0.14	6	36.14 ± 2.26	3.922 ± 0.103
9204	Plagioclase-Composite[1]	0.07	1	36.56 ± 0.61	3.940 ± 0.035
9212	Pyroxene[1]	0.03	2	30.49 ± 1.17	3.653 ± 0.064
9246	Matrix[1]	0.12	2	32.98 ± 0.33	3.776 ± 0.027
8194	Feldsparthoid[2]	6	<10	34.66 ± 0.99	3.902 ± 0.042
8204	Feldsparthoid[2]	6	<10	31.10 ± 0.75	3.734 ± 0.050
8212	Feldsparthoid[2]	9	<10	35.03 ± 0.60	3.923 ± 0.043
8214	Feldsparthoid[2]	3	<10	35.40 ± 1.80	3.940 ± 0.088
8242	Feldsparthoid[2]	3	<10	33.77 ± 1.30	3.864 ± 0.070
8244	Feldsparthoid[2]	8	<10	34.29 ± 0.55	3.889 ± 0.041
8248	Feldsparthoid[2]	5	<10	35.76 ± 0.80	3.954 ± 0.050

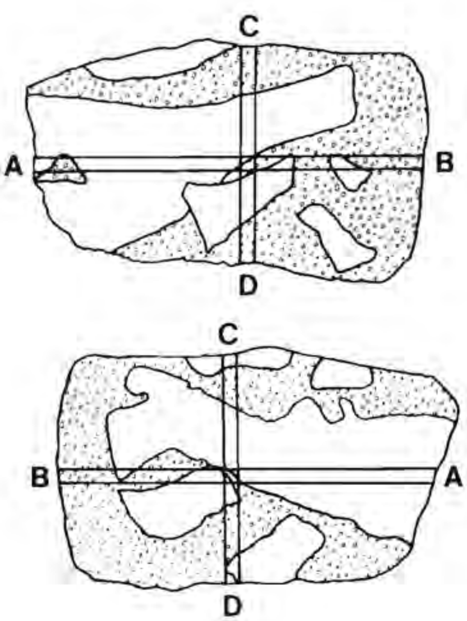
[1] None preheating. Sample degassed at 225°C during bakeout after sample loading.

[2] Sample preheated at 650°C for 3 hours and then degassed at 225°C during bakeout after sample loading.

THERMOLUMINESCENCE OF A GAS-RICH METEORITE AND THE RELATIONSHIP BETWEEN GAS-RICH AND GAS-POOR METEORITES. Derek W.G. Sears, Department of Chemistry, University of Arkansas, Fayetteville, AR 72701.

The thermoluminescence (TL) sensitivity of 79 samples from the Plainview gas-rich meteorite have been used to derive new information on the nature of the dark matrix. The samples came from two bars which had been cut from a 4 mm thick slice (BM 1959,805) measuring 4.0 x 6.5 cm (Fig. 1). An approximately equal number of samples were taken from the dark matrix and light clasts. The TL sensitivity was measured by heating the samples to 500°C, to drain their natural TL, and then giving them a 50 krad radiation dose from a ^{60}Co γ source prior to TL measurement.

TL sensitivity is very susceptible to small changes in the crystallography of feldspar, which is the TL phosphor. For example, type 3 meteorites have a TL sensitivity 10^{-5} (type 3.0) to 10^{-2} (type 3.9) times that of type 6 meteorites (Sears et al., 1980) and shock-blackened ordinary chondrites have a TL sensitivity $\sim 10^{-2}$ times that of unshocked meteorites of the same petrologic type (Sears, 1980). Fig. 2 shows how the TL sensitivity varied along each bar; open circles refer to samples taken from light clasts, filled circles to dark matrix samples and dots refer to samples which are matrix on one side of the slice and clast on the other. The average TL sensitivity of samples from dark matrix was 1.36 ± 0.48 (where the units are arbitrary and



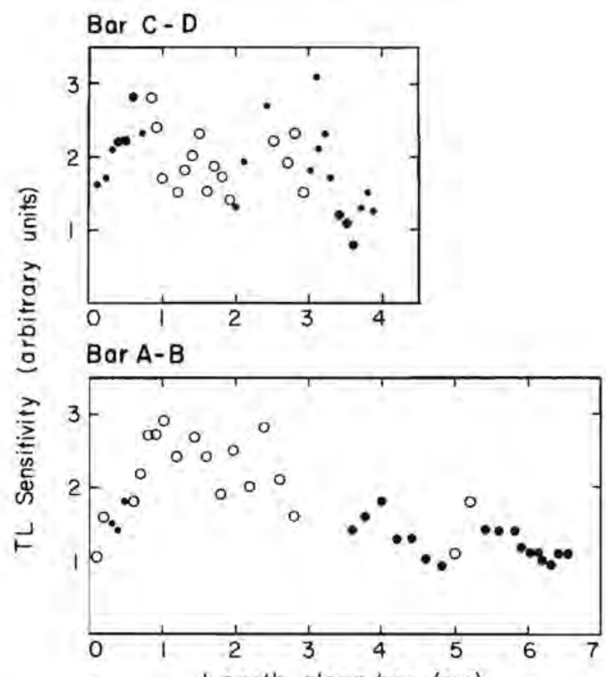


FIG. 1 (left) The 4.0 x 6.0 x 0.4 cm slice from the Plainview meteorite used for the present study. The light clasts, dark matrix and sampling bars are indicated. Fig. 2 (right) TL sensitivity along the two bars shown in Fig. 1. Filled circles refer to dark matrix samples, open circles to light clast material and dots to samples which were matrix on one side of the slice and clast on the other, or were otherwise uncertain.

the errors are one standard deviation). For the clasts these figures are 2.02 ± 0.50. It is concluded that a major fraction of the material in the dark matrix is relatively unshocked and comparable to the clasts in the extent of equilibration. The slightly lower TL in the matrix may be due to 1) the lower albedo of the matrix, since much of the TL detected will have suffered multiple reflections with grain surfaces, or 2) the equilibrated material being diluted with an equal amount of material with much lower TL; the dilutant could be either type 3 material (Noonan and Nelen, 1976; A. Rubin, per. comm.) or clast material whose feldspar has been turned to maskelynite by the regolith process (Ashworth and Barber, 1976). Expanation (1) is thought unlikely, since, to the naked eye at least, the albedo difference in these samples is very subtle. Whichever is the case, it is concluded that at least ∿70% of the dark matrix is as equilibrated as the clasts.

The source of the equilibrated material in the dark matrix is probably comminuted clast material. In contrast, the matrix of Mezö Madaras, a gas-poor breccia, has a TL sensitivity consistent with its type 3 assignment (Sears et al., 1980; Binns, 1968; Van Schmus, 1967). Gas-rich breccias also differ from gas-poor breccias in being rich in solar gases, charged-particle tracks and carbon (Suess et al., 1964). On the other hand, gas-rich and gas-poor breccias are similar in that they are both surface regoliths, evidence for this is their structure and the presence of shocked and xenolithic fragments in the matrix. The degree of comminution of the matrix, the abundance of solar wind carbon and the amount of glass have been used as indices of regolith maturity in lunar studies (e.g., King, 1977). It is therefore suggested that the main difference between gas-rich and gas-poor meteorite breccias is that the former come from much more mature regoliths (Sears, 1981).

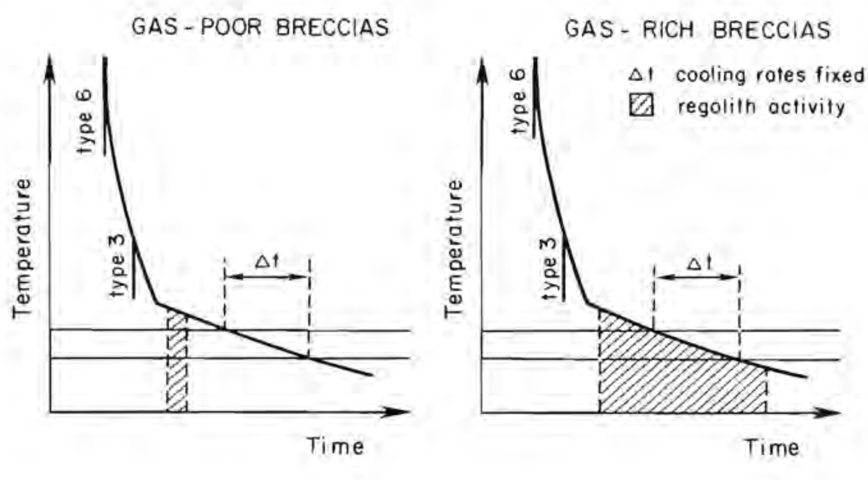


FIG. 3 Schematic diagrams to show a possible relationship between gas-rich and gas-poor meteorite breccias. It is suggested that the difference is one of regolith maturity and that brecciation continued until temperatures had fallen below those at which metallographic cooling rates are fixed in the case of gas-rich meteorites.

Metallographic data have been published for eight regolith breccias, three gas-poor and five gas-rich (Wood, 1967; Scott and Rajan, 1980). One may generalize from the data that gas-poor breccias produce coherent metal composition plots, while gas-rich breccias do not; incoherent composition-dimension plots may imply brecciation after cooling below the temperatures at which metallographic cooling rates were fixed. This observation is consistent with a maturity difference between gas-rich and gas-poor breccias and suggests the time-temperature histories in Fig. 3.

The matrix of gas-rich breccias may be of any petrologic type (see Keil, this volume, for specific examples). The many type 3 meteorites which contain true xenoliths and equilibrated clasts are also regolith breccias and at least one even contains solar wind gases (see Scott and Taylor, this volume). Apparently, these generally gas-poor meteorites are immature regolith breccias which, after appropriately long regolith lifetime, would resemble gas-rich meteorites like Dimmitt, with a low petrologic type matrix. Dimmitt even contains graphite-magnetite inclusions similar to those found in certain type 3 meteorites; the more delicate type 3 characteristics, such as fine-grained ("Huss") matrix, would almost certainly not survive regolith activity for very long. I believe it is misleading to term such meteorites "primitive breccias" as this implies the major difference between meteorites which are gas-poor and primarily type 3 (e.g., Mezö-Madaras) and those which are gas-rich and contain a matrix which is a mixture of type 3 material and comminuted matrix (e.g., Weston) is associated with metamorphism. In fact, the differences are associated with the maturity of the regolith.

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PRIMITIVE BRECCIAS AMONG TYPE 3 ORDINARY CHONDRITES - ORIGIN AND RELATION TO REGOLITH BRECCIAS

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Binns (1967a) found that among ordinary chondrites 25% of H, 10% of L and 62% of LL chondrites were breccias containing rock clasts. Many (∿ 40) including Weston (Noonan and Nelen, 1976) contain solar-wind gases and solar-flare tracks and are called regolith breccias (see Keil, Taylor, this volume). About 14% of all H chondrites are "gas-rich", 3% of all L and 8% of all LL chondrites (Wasson, 1974, p. 104; Crabb and Schultz, 1981). In addition there are "gas-poor" fragmental breccias with similar dark hosts and light clasts such as Kelly (Bunch and Stöffler, 1974), Castalia (Van Schmus, 1969) and L'Aigle (Hintenberger et al., 1964). We wish to define a new kind of ordinary chondrite breccia, 'primitive breccias'. These have matrices composed almost entirely of the primitive components found in type 3 chondrites including chondrules and opaque and recrystallized, fine-grained silicate matrix. [We call the latter 'Huss matrix' to distinguish it from the breccia matrix: Huss et al. (1981) studied it in some detail.] Some primitive breccias contain solar-wind gases but most appear to be gas-poor. Although some primitive breccias may have formed before some regolith breccias, we do not wish to imply that they are all older.

Primitive breccias. Table 1 lists 7 ordinary chondrite primitive breccias, which comprise about half of all well-studied type 3 ordinary chondrites (Dodd et al., 1967). Like the regolith breccias, they may contain clasts of type 3-6 chondrites, carbonaceous and impact-melted material, but their matrices have two distinctive features. They contain a) ⩾ 50 vol% of chondrules and recognizable chondrule fragments c.f. ∿ 20% in regolith breccias (Noonan and Nelen, 1976), and b) 10-16 vol% Huss matrix (Huss et al., 1981) c.f. < 1% in regolith breccias (Fig. 1).

Both cm and mm sized clasts are much more abundant in regolith breccias than in primitive breccias. (Further study may therefore reveal more type 3 chondrites that are primitive breccias.) Both kinds of breccia have unequilibrated silicates in their matrices: typically 5-30 mole % Fa in olivine. Except for the most unequilibrated type 3 chondrites like Krymka, matrices in both kinds of breccias also have compositions which cluster near the compositions for equilibrated members of the chondrite class. However, matrices of regolith breccias appear to be mixtures of roughly equal proportions of equilibrated and unequilibrated chondritic material (Noonan and Nelen, 1976; McSween and Lipschutz, 1980; Rubin et al., 1981).

Metallographic cooling rates and times of breccia formation.

Studies of Ni concentrations in taenite grains provide estimates of cooling rates in the temperature range ∿ 750-550 K (Wood, 1967). Taenite grains in the matrix of a single regolith breccia show a wide range of cooling rates, e.g., 1-100 K/Myr, indicating that these cooled through 700 K in separate environments before consolidation of the breccia (Scott and Rajan, 1981). Some primitive breccias such as Ngawi and Allan Hills A77278 show similar wide ranges of cooling rates (Table 1), and therefore are also composed of material that cooled at very different burial depths. The Ngawi breccia must have formed more recently than 4.4 Gyr ago, allowing 100 Myr for cooling at say 2 K/Myr through 200 K. Mezö-Madaras, however, formed before its parent body had cooled through 750 K, as shown by the uniformity of taenite cooling rates.

PRIMITIVE BRECCIAS

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Table 1. Primitive chondrite breccias

Meteorite	Host*	Clasts	Cooling rates† in host K/Myr	References for clasts
Sharps	H3.4	C		Fredriksson et al. 1967
Bremervörde	H3.9	H3,H4,H5		Binns 1968, Wlotzka 1974 Hutchison et al. 1981
Mező-Madaras	L3.7	L4,CM,Me	1	VanSchmus 1967,Binns 1968
Krymka	LL3.0	C	1	Grossman et al. 1980
Ngawi	LL3.6	LL4,LL6, frag.brec.	1-300	this work
Parnallee	LL3.6	Me		Wahl 1952, Binns 1967b
ALHA77278	LL3.6		10-1000	

* Sears et al. (1980, 1981) † This work except MM (Scott and Rajan, 1981)
Me - impact melted clast.

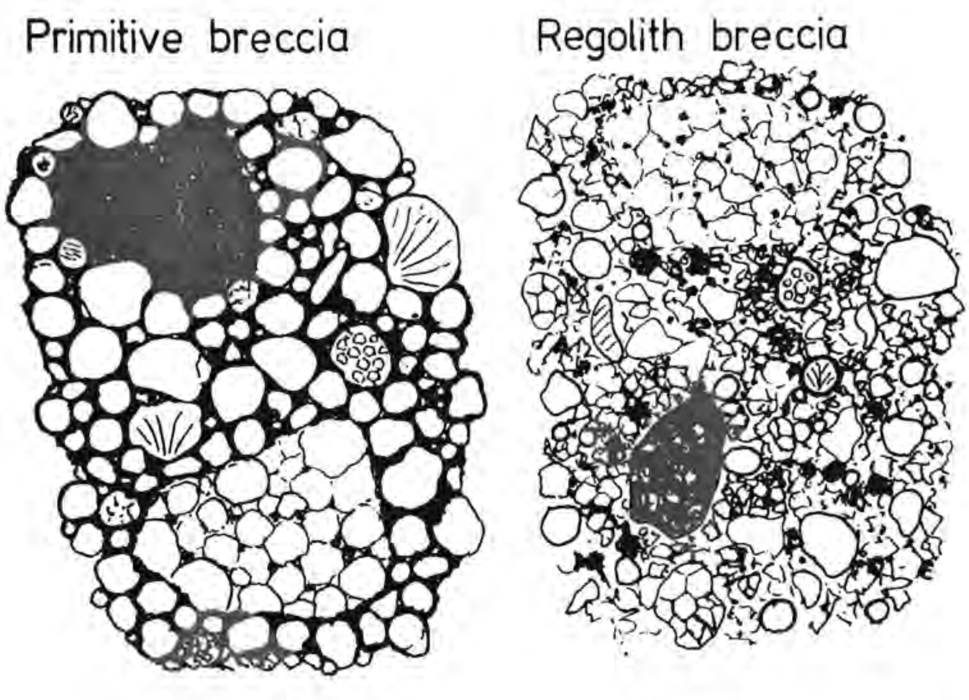

Fig.1 Primitive breccias have matrices made of mm-sized chondrules and opaque, fine-grained,silicate matrix and metal, typical of type 3 chondrites, whereas regolith breccias have matrices made of rock fragments, metal and fewer chondrules. Clasts shown: left, carbonaceous and type 4; right, type 5, shock-blackened & many others.

Primitive breccias

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Origins of primitive breccias

1. In a broad sense, the unconsolidated (or weakly consolidated) primitive components (chondrules, Huss matrix, etc) and clasts from which the primitive breccias formed could be called a regolith. At least one primitive breccia, Bremervörde, contains solar-wind gas (Schultz and Kruse, 1975). However, it is not clear when the solar-wind gas in this meteorite was acquired, as Bremervörde differs greatly from regolith breccias like Weston et al. If the solar-wind gases were acquired on the surface of the H parent body or an H planetesimal, the regolith was very immature by comparison with the regolith from which Weston et al. formed. Because of the similarities between lunar breccias and Weston et al., and the very different nature of the primitive breccias we reserve the term 'regolith breccia' for Weston et al.

2. Primitive breccias could have formed on parent body or planetesimal surfaces before regolith breccias. However, the presence of a fragmental breccia clast within Ngawi suggests that the two types of breccia did not form sequentially.

3. We suggest that primitive breccias formed inside parent bodies by mixing of rock fragments with much larger proportions of unconsolidated primitive components. This mixing might be a result of disruption and reassembly of asteroids (Davis and Chapman, 1977; Hartmann 1979) or spallation by seismic waves (Hörz and Schaal, 1981). Opportunities for mixing of diverse materials in this way would be greatly enhanced if metamorphism occurred in planetesimals before accretion was complete (Scott and Rajan, 1981). Thus primitive breccias may have formed within asteroids, whereas regolith breccias formed on their surfaces. A model such as this in which the two kinds of breccia have very different origins is consistent with the apparent absence of intermediate kinds.

Other implications

1. Unequilibrated material in the matrices of regolith breccias could have been derived by fragmentation of unconsolidated primitive components. The abundance of this material and the general lack of type 3 clasts in regolith breccias could thus be a result of the high proportion of unconsolidated primitive components in chondrite parent bodies. Much regolith material on chondritic parent bodies could then have been derived from primitive dust, and not all from comminuted rocks as commonly believed.

2. The presence of appreciable quantities of primitive dust in chondritic asteroids would greatly affect their physical strength and thermal conductivity (Wood, 1979). Perhaps some asteroids still retain some primitive dust.

3. Some carbonaceous type 3 chondrites such as Leoville (Keil et al., 1969), Kakangari (anomalous type 3, Srinivasan and Anders, 1977) and Vigarano may also be primitive breccias according to our definition. The two latter contain solar-wind gas.

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ABOUT REGOLITH DYNAMICS AND THE ANCIENT SOLAR CORPUSCULAR RADIATION; POTENTIAL OF LUNAR AND METEORITIC STUDIES. P. Signer, Ph. Etique, R. Wieler, Swiss Federal Institute of Technology ETH, Sonneggstrasse 5, CH-8092 Zürich.

The information on regolith dynamics and parameters of the ancient solar corpuscular radiation to be gained from the intricate records in lunar soils, breccias and gas-rich meteorites has initiated a large number of studies of such material. For a number of years, we have studied noble gases and tracks in lunar samples to retrieve such records and summarize here some of the facts and conclusions.

Our investigations of He, Ne, and Ar in handpicked 150-200 μm plagioclases, olivines/pyroxenes and ilmenites as well as agglutinates and breccias separated from 15 surface soils, 6 drill core soils and 2 soil breccias lead to the following experimental observations:

1 Signer et al. (1977) showed that ^{36}Ar concentrations in minerals are 10 - 50 % of those in equally sized breccias and even as little as 2 - 12 % of those in agglutinates. Furthermore, all minerals separated from the same soil have similar ^{36}Ar concentrations (except in very gas-poor soils). The plagioclases contain on average about 25 % less ^{36}Ar than ilmenites and olivines/pyroxenes. In the minerals studied, the ^{36}Ar concentrations range between some 5 and $3000 \times 10^{-8} cm^3 STP/g$, which amounts to about $1\text{-}800 \times 10^{10}$ ^{36}Ar atoms/cm^2 grain surface. The concentrations in minerals do not correlate to those in the agglutinates from the same soil.

2 He and Ar analyses in about 80 single plagioclase grains from a gas-rich and a gas-poor soil showed that in both cases all grains contain solar gases. The concentrations range over more than an order of magnitude (Wieler et al., 1980; Wieler, 1981).

3 The ranges of the He/Ar and Ne/Ar ratios are mineral-specific (table 1). The few samples investigated also for Kr and Xe show, within a factor of about 2, no mineral-specific Ar/Kr/Xe patterns (Signer et al., 1977; Wieler, 1981). The abundance ratios of these gases are, however, not solar.

4 The $^{20}Ne/^{22}Ne$ ratios of the solar Ne*) depend slightly on the host mineral. In ilmenites and olivines/pyroxenes from surface soils, drill core soils and soil breccias, the solar $^{20}Ne/^{22}Ne$ are equal within about 2 %. However, plagioclases extracted from surface soils tend to have higher solar $^{20}Ne/^{22}Ne$ ratios than plagioclases separated from soils not recently exposed (Wieler and Signer, 1981).

5 The ^{36}Ar concentration correlates within about 20 % with the percentage of track-rich grains and the mean central track density in aliquot plagioclase separates from surface soils (Wieler et al., 1980). Exception to this are plagioclases from the not recently exposed drill core soil 15002,50, which contain about twice as many tracks relative to ^{36}Ar.

Our studies of the noble gas distribution in plagioclases from soil 61501 by etching different grain-size fractions to various depth (Etique et al., 1979; Etique, 1981; Etique et al., 1981; Etique and Signer, 1981) showed:

6 Plagioclases etched to about 1 μm contain up to 10 % of the solar gas of the unetched minerals. Grains etched to more than 30 μm nominal depth still contain traces of solar-type Ne.

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*) The isotopic compositions of the implanted and retained solar wind Ne were deduced by assuming a 2-component superposition with the mineral-specific composition of the spallogenic Ne according to Lugmair et al. (1976).

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7 The $^{20}Ne/^{22}Ne$ and $^{36}Ar/^{38}Ar$ ratios of the gas lost in the ∿1 µm etchings were distinctly higher (12.6 and 5.5, respectively) than the values extrapolated for the solar component from the unetched grain-size suite (11.9 and 5.4, respectively).

8 In a 3-isotope correlation plot, the Ne data of the etched grains define a linear array with a correlation coefficient of 0.998.

Our favoured interpretations and conclusions of the above experimental observations are:

● (1) shows that solar gas concentrations in bulk soils are dominated by those in agglutinates and breccias. The similarity of the ^{36}Ar concentrations in all minerals from one soil and the Ar/Kr/Xe ratios in minerals and agglutinates imply that even plagioclase has retained more than 2/3 of the implanted Ar. This seems reasonable because the ^{36}Ar surface concentrations in the minerals are below saturation. The mineral-specific He/Ar and Ne/Ar ratios (3) are the result of mineral-specific diffusive losses of He and Ne. Such diffusion takes place predominantly while the grains reside near the regolith surface (Wieler et al., 1979).

● The comparatively low ^{36}Ar concentrations in minerals (1) imply a short time of solar wind exposure (10^3-10^4 years). From (2) we conclude that this "acquisition time" is composed of many individual "exposure episodes". Investigations of soils with known excavation ages showed that the individual exposure episodes are spread over a time of several 10^7 years. These conclusions are in accord with deductions from model calculations by Borg et al. (1976). Mineral grains have, as discrete particles on the regolith surface, short lifetimes against destruction (around 10^4 years for 150-200 µm grains; Signer et al., 1977). However, since mineral grains are present in all lunar soils, they also must be constantly replenished by erosion of larger grains or rocks. As a consequence of this wear-down process of minerals, each grain has surface parts of different ages. Therefore, for minerals from a given soil, no reason exists for implanted gases to have grain-size independent surface concentrations. Moreover, independent evolutions of minerals and coexisting breccias and agglutinates are possible, which explains the lack of a correlation between ^{36}Ar concentrations in primary and secondary particles.

TABLE 1

Sample type	^{36}Ar concentrations ($\times 10^{-8}$ cm^3/g)	$^4He/^{36}Ar$	$^{20}Ne/^{36}Ar$
Lunar bulk soils			
< 1000 µm	16000-43000	Mare 200- 1200	4.4-10.6
		Highl. 60- 110	2.2- 3.2
150-200 µm	3000-17000		
Lunar soil minerals			
Plagioclase	5- 3000	Mare 80- 300	1.6- 2.8
		Highl. 40- 110	0.7- 2.0
Olivine/pyroxene	30- 3400	200- 750	5.2-18.0
Ilmenite	700- 3350	4400-11000	20.0-28.0
Meteorites			
Khor Temiki	10	17000	56
Kapoeta	100	1300	17
Solar abundances (Cameron, 1981)	---	20200	26

● Observation (4) indicates, on the one hand, that the isotopic composition of solar wind Ne was constant within 2 % over billions of years. On the other hand, the $^{20}Ne/^{22}Ne$ ratios of etched plagioclases (8) strongly indicate a mixture of a solar-type Ne with a $^{20}Ne/^{22}Ne$ ratio of 11.3 ± 0.2 and GCR spallation Ne. The unetched grains contain, in addition, surficially retained solar wind Ne with a ratio >12.6. The trend to lower values in not recently exposed soils (4) is interpreted as due to solar flare implanted Ne (Etique, 1981; Etique et al., 1981; Etique and Signer, 1981; Wieler and Signer, 1981). If the solar Ne in etched grains consists of flare implanted Ne only, then the $^{20}Ne/^{22}Ne$ ratio in flares is 11.3. This value is higher than the ratio measured by satellite borne instruments (Dietrich and Simpson, 1979; Mewaldt et al., 1979), possibly because of the different energy ranges sampled or the different sampling periods. We can not exclude, however, that the solar Ne in the etched grains is a mixture of migrated solar wind and solar flare Ne. In this case, the $^{20}Ne/^{22}Ne$ ratio of the flare component would be smaller than 11.3.

Concerning noble gases in bulk samples from regolithic meteorites, one notes that

1 Concentration of solar gases in bulk samples range well below those in lunar soils (table 1).

2 Element abundances in certain meteorites appear to be less fractionated than those in lunar bulk soils (table 1).

3 The $^{20}Ne/^{22}Ne$ ratios of solar Ne in some gas-rich meteorites are lower than in lunar soils.

In the light of the lunar soil studies, these observations can be interpreted as follows:

- The comparatively low concentrations of solar gases are in accord with the low maturity of the regolith from which gas-rich meteorites are formed and presumably reflect the differences in the regolith dynamics on the Moon and meteorite parent bodies.
- As seen from table 1 the noble gas patterns of the meteorites cannot be synthesized from the patterns in lunar minerals. A cause for this could be smaller diffusive loss of He and Ne in the regolith on a meteorite parent body (lower temperatures during gas acquisition).
- The $^{20}Ne/^{22}Ne$ ratios of the non-spallogenic Ne in meteorites may not indicate an enhanced contribution of Ne trapped from solar flares as in the case of lunar plagioclases. First, because on a meteorite parent body the retention of solar He and Ne is comparable to that in ilmenites on the Moon, a contribution of flare implanted gases (especially Ne) is expected to be masked. Secondly, an admixture of planetary-type Ne ($^{20}Ne/^{22}Ne \sim 8$) would also cause low $^{20}Ne/^{22}Ne$ values.

In summary, we note that mineral separates are superior to bulk samples for studies of properties of the ancient solar corpuscular radiation, because individual primary particles come and go rapidly near the regolith surface, whereas secondary matter is comminuted during all surface exposures. However, some of our conclusions hinge on the claim that solar wind Ar is well retained in minerals. In view of the low Ar/N ratios measured in bulk samples (c.f. Kerridge, 1980; Clayton and Thiemens, 1980) our claim is controversal and calls for Ar/N measurements on mineral separates. Whether or not lunar minerals retain at least Ar reasonably well, it is desirable to investigate mineral separates rather than bulk samples from lunar soils and breccias as well as from regolithic meteorites. Results of such comparative studies are expected to further the understanding of the differences between the regolith on the Moon and on meteorite parent bodies as well as the characteristics of the ancient solar corpuscular radiation.

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TERRESTRIAL IMPACT BRECCIAS. D. Stöffler, Institute of Mineralogy, University of Münster, D-4400 Münster, W.-Germany.

Introduction. Impacts on Earth have occured in a great variety of target rocks. The targets are generally heterogenous with respect to structural and compositional properties (complexes of metamorphic and igneous rocks, stratified sedimentary rocks or a combination of both). The propagation of the shock wave, the subsequent particle motion in the affected target volume, and the subsequent breccia formation will be influenced by (a) the Hugoniot equations of state of the target materials, (b) the abundance and spatial orientation of density discontinuities (fractures, bedding planes, schistosity etc.), (c) the (micro)porosity, (d) the material strength, (e) the volatile contents, and (f) the abundance of material (e.g. carbonate rocks) which decomposes incongruently rather than melts congruently upon release from very high shock pressure. Breccia formation will also be governed by parameters which characterize the projectile and the impact conditions. These are (a) size, density and composition of the projectile, (b) velocity of impact, and (c) angle of impact. The first two parameters determine the size of the resulting crater.

The understanding of these effects on breccia formation is still very limited and unsatisfactory for terrestrial cratering and is based almost exclusively on empirical data from field and laboratory observations on craters and breccia samples. The theory of cratering mechanics and the level of hypervelocity cratering experimentation is not yet advanced enough to model all of these parameters quantitatively. Therefore, the problem of breccia formation in terrestrial craters will be approached from an observational data base in the following discussion. In this approach only the following parameters can be varied: target structure, target composition and crater size. To some degree the composition of the projectile is also a variable.

Classification of impact formations and breccia textures

With increasing size the morphological type of a terrestrial crater changes from: a) simple, bowl-shaped to b) flat-floored, complex with central peak, and c) flat-floored, complex with ring structures (Dence et al., 1977).

Morphologically and with respect to the structural elements of a crater, we may subdivide the displaced and brecciated rocks into inner impact formations inside the crater rim, and outer impact formations outside the rim (Stöffler et al., 1979). Structurally, three types of impact formations can be distinguished: (I) Allochthonous layers of breccias, (II) intrusive breccia dikes, and (III) autochthonous breccias and shocked basement rocks. Texturally, these formations are heterogeneous and consist of a variety of basic textural components if the texture is also considered at the microscopic level. This leads to the identification of six textural types of breccias (Stöffler et al., 1979). These are: (a) fragmental breccias (polymict), (b) suevitic breccias with clastic matrix and cogenetic melt inclusions (polymict), (c) impact melt breccias or melt rocks with semi-or holocrystalline matrix and clastic inclusions (polymict), (d) impact glasses with hyaline to semicrystalline (devitrified) matrix and clastic inclusions (polymict), (e) cataclastic rocks (monomict breccias), and (f) shocked target rocks (unbrecciated but shock metamorphosed in the solid state). Regarding the shock and thermal history of these breccias, only types (e) and (f) and the melt fraction of types (c) and (d) can be characterized by a uniform peak pressure and temperature whereas breccia types (a) - (d) have complex shock and thermal histories (Table 1), i.e. they consist of a mixture or rock fragments of different peak pressure and temperature which leads to an equilibrium temperature by heat exchange between the rock fragments after the breccia was formed and deposited.

These textural types of breccia form either independent units within the impact formations of a crater or they are components of other breccia types (Stöffler et al., 1979) (Table 2). This fact results in characteristic breccia-in-breccia textures.

Geologic setting of breccias.

A few characteristics of the geological setting of the breccia types are common to all craters irrespective of their size, and type of target except for non-cohesive target materials (Table 2 and 3, Fig. 1) (Stöffler, 1981). Fragmental breccias of variable clast size form the bulk of the ejecta blanket and of the crater fill (breccia lens) in all consolidated target rocks. Coherent sheets of melt breccias and/or suevitic breccias are major components of the breccia lens in the cavity and rim area of craters in targets from which melts have been produced by shock. Suevite is also found beyond the rim on top of fragmental breccias in craters such as the Ries and Popigai. The crater basement below the breccia lens consists of autochthonous shocked rocks and monomict breccias which are commonly dissected by various types of breccia dikes ranging in texture from purely clastic and suevitic to melt breccia types. The frequency, composition, texture and geologic setting of the various breccias is variable from crater to crater as a function of its size and type of target.

Parameters of breccia formation.

Target strength. The degree of cohesion of the target material has a most fundamental influence on breccia formation. A special case is non-cohesive targets which yield none of the breccia types described above for coherent target rocks. Instead, "breccias" formed by shock lithification or shock fusion of the particulate material, as well as comminuted particles, are the typical impact formations. Good examples of hypervelocity terrestrial craters of this type are rare (Wabar). The impact formations we can expect from these craters are best demonstrated by experimental craters in sand (Stöffler et al., 1975). The types of shock-induced formations and their abundances and distribution at the parent crater are given in Table 3.

With increasing cohesiveness of the target rocks blocky rims and blocky ejecta blankets appear. If the target material is composed of consolidated rocks, the typical suite of polymict and monomict breccias described above, will be formed upon cratering. The influence of fractures, joints, and density discontinuites on the breccia forming processes appears to be important but is not known in any detail. Strong heterogeneties in the azimuthal and radial distribution of target rocks in the ejecta blanket as observed in the Ries (Pohl et al., 1977) may be due to these effects.

Target composition. The most conspicuous effect of the target composition on breccia formation results from the abundance of water and of mineral components which decompose incongruently upon shock compression such as carbonates and certain (OH)-bearing minerals (Kieffer and Simonds, 1980). Consequently, limestone-rich targets yield enormous volumes of vapor instead of melts. This explains the lack of impact melt and suevitic breccia formations in terrestrial craters with limestone targets. It appears that the formation of coherent melt sheets, typical for craters in crystalline rocks, is more and more replaced by the formation of suevitic breccias if the fraction of volatile-producing target rocks is increased (Kieffer and Simonds, 1980). This is best documented by the dominance of suevite at Popigai and Ries craters (Masaitis et al., 1975; Pohl et al., 1977) which have thick sedimentary rock strata on top of crystalline basements. It should be emphasized however, that a certain fraction of melt is always present in the form of suevitic breccia, even if the target is exclusively composed of crystalline rocks.

Crater size. The change of the composition, texture, and distribution of breccias with increasing crater size is only known reasonably well for the inner impact formations of craters in crystalline rock targets (Dence et al., 1977; Grieve et al., 1977). In simple craters (e.g. Lonar Lake, Brent) highly polymict clastic breccias with melt inclusions are concentrated in the upper central part and in the lower part of the breccia lens. These suevitic breccias are interlayered with less polymict and less shocked clastic breccias which contain coarse blocks and which grade into monomict breccias toward the crater rim and at the bottom of the breccia lens. The melt at complex central peak craters forms a coherent layer which rests directly upon the shocked basement of the central uplift and extends laterally over suevitic and clastic breccias toward the rim. Dikes of these three textural types of breccias are found in the crater basement. Breccia types are not significantly different in complex ring structures. Their distribution differs from central peak craters only in the fact that the coherent melt sheet and the underlying suevitic and clastic breccias are confined to a ring structure located between the central uplifted basement and a peripheral trough extending to the crater rim area as a graben-like structure. In the case of mixed targets (sedimentary rocks on crystalline basement) the suevite breccia dominating the crater fill at medium sized craters appears to be replaced partly at large craters by discontinous layers of melt rocks in the top section of the breccias lens and as dikes, necks, and irregular injections in deeper parts of the breccia (Pohl et al., 1977; Masaitis et al., 1975).

Petrography of polymict breccias

Fragmental breccias. From the limited data available for fragmental breccias of the outer impact formation the following major characteristics seem to be most relevant. The abundance of weakly and moderately shocked clasts is very low. Consequently, the heat content of fragmental breccia units was extremely low (Table 1). Some properties vary with radial range: the block (clast) size (Table 4) decreases, the fraction of clasts from the upper target section and the amount of local material incorporated into the breccia by secondary mass wasting (Hörz et al., 1977) increases. In vertical sections the clast size decreases whereas the fraction of clasts from the lower target section and the fraction of slightly shocked clasts increases from bottom to top. Fragmental breccias from the inner impact formations display a decreasing degree of mixing and increasing clast size from the center toward the margin and from top to bottom of the breccia lens. Clasts are derived from deeper stratigraphic levels of the target compared to those in breccias of the ejecta blanket. Dikes dissecting the crater basement and displaced megablocks represent a third variety of fragmental breccia (Stöffler et al., 1977; Stöffler et al., 1979; Lambert, 1981).

Suevitic breccias. Suevitic breccias consist of rock and mineral clasts (up to decimeters in size, Table 4) of all stages of shock metamorphism (including shock-fused rocks). The melt has a uniform composition which closely matches the composition of the target rocks (Masaitis et al., 1975; Grieve et al., 1977; Engelhardt, 1972; Reimold, 1980). The abundance and size of melt inclusions (Table 2) in the suevitic breccias of the crater fill decreases with increasing depth and lateral distance from the center (Grieve, 1978; Stöffler, 1977). These breccias grade into very melt-rich varieties which are genetically linked to coherent, fragment-laden melt rocks. Melt "bombs" shaped by ballistic ejection are only found in suevite of the outer impact formations.

Impact melt breccias. Impact melt breccias in crystalline rock targets consist of a very fine to medium-grained igneous-textured matrix with variable amounts of lithic and mineral clasts affected by variable degrees of shock and thermal metamorphism. The melt rock matrix crystallized from a superheated melt at relatively low water vapor pressure to form An-rich plagioclase, orthopyroxene and/or augite, sanidine, quartz and mesostasis. A typical section of an impact melt sheet displays decreasing clast-content and increasing grain size of the matrix from both the lower and upper boundary towards the central part (Grieve et al., 1977). Most characteristic is the lack of any fractionation within melt sheets (up to 230 m thickness). In no case has an impact melt formed by partial melting of target rocks been observed macroscopically. Such melts may be found very locally as intergranular melts with lithic clast inclusions.

Chemistry of impact melts.

Impact melts are formed well above the liquidus temperature (Table 1). They are highly turbulent, rapidly moving liquids (particle velocities up to kilometers per second) of extremely low viscosity (<10 Poise) before they get mixed with clastic debris of low heat content (Grieve et al., 1977; Onorato et al., 1978). This explains their extreme homogeneity (Table 5) which has been observed not only in coherent melt sheets with volumes of up to several 100 km^3 but also in widely dispersed melt inclusions of suevitic breccias, although the target rock composition is extremely heterogenous (Table 5; 14, 15, 16, 17, 11, 7, 8, 18, 19, 20, 21, 22). In a number of terrestrial impact melts contamination by the impacting projectile was detected and the composition of the projectile could be derived (Palme, 1980). The composition of the analyzed impact melt has been successfully modelled for various craters by a mixture of crater basement rocks and the projectile (Grieve, 1978; Grieve, 1975; Grieve and Floran, 1978, Reimold et al, 1980; Reimold, 1980). The perfect homogenization of melt in large craters is not duplicated in small craters such as Lonar Lake, Monturaqui, and Tenoumer which produced only small quantities of melt. Melt samples from these craters show considerable variation in chemical composition and distinct deviations from the target rock composition (Grieve et al., 1977).

Isotope equilibration in impact melts and suevitic breccias. Shock melting is capable of resetting the isotope systems which are used for age dating, i.e. analyses of impact melts yield correct ages of the related impact events. This is not the case with rocks and minerals of lower stages of shock metamorphism (< 50-55 GPa; (Jessberger et al., 1978; Jessberger and Ostertag, 1981; Davis, 1977)). However, lithic clasts of the shock range 25-50 GPa which were thermally metamorphosed either in impact melts or suevites (Table 1) display disturbed Rb-Sr- (Reimold, 1980) and K-Ar-systems (Bogard et al., 1981) which may lead to a resetting of the primary age of the clasts. It is important to note that any reaction of the isotope systems of rocks to impact metamorphism is restricted to a small volume of the total displaced mass of a crater of no more than 3 - 7 %.

Relative abundances of breccia types. As seen from Table 2 fragmental breccias which are typified by a low or undetecable degree of shock, low heat content, and undisturbed isotope characteristics are by far the most abundant allochthonous impact formation at any crater. All other allochthonous formations comprise a total volume of less than about 10 % of the volume of displaced rocks including 0.5 - 5 % of impact melt. There is some indication that the fraction of melt increases somewhat with increasing size of a crater; it certainly does if only the volume of the crater fill is considered (Grieve et al., 1977; Kieffer and Simonds, 1980). In targets with carbonate lithologies impact melt is totally lacking so that the fraction of fragmental breccias approaches 100 %.

TABLE 1: SHOCK AND THERMAL HISTORY OF BRECCIAS FORMED FROM SILICATE ROCKS

SHOCKED ROCK OR BRECCIA TYPE	PEAK SHOCK GPa	MAXIMUM POST-SHOCK TEMPERATURE °C	POST-DEPOSITIONAL EQUILIBRIUM TEMPERATURE °C	COOLING TIME
CATACLASTIC ROCKS	< 5 - 10	< 50	-	YEARS
SHOCKED ROCK (STAGE I)	10 - 30	50 - 200	-	
SHOCKED ROCK (STAGE II)	30 - 45	200 - 800	-	
SHOCKED ROCK (STAGE III)	45 - 60	800 -1500?	-	
IMPACT MELT	60 - 80	1500 -3000?	-	
FRAGMENTAL BRECCIA	VARIABLE (< 40)	VARIABLE (< 500)	< 50	
SUEVITIC BRECCIA	VARIABLE (< 100)	VARIABLE (< 3000)	400 - 800 (DEPENDING ON MELT CONTENT OF SUEVITE)	MONTHS TO YEARS
IMPACT MELT BRECCIAS	VARIABLE (< 100)	VARIABLE (< 3000)	900 - 1200	YEARS TO 10^3 YEARS
IMPACT GLASSES	VARIABLE (< 100)	VARIABLE (< 3000)	900 - 1200	MINUTES

DATA SOURCES: (27), (28), (12), (20), (18), (21)

TABLE 2: GEOLOGIC SETTING OF BRECCIA TYPES AT TERRESTRIAL IMPACT CRATERS IN CONSOLIDATED TARGETS

BRECCIA TYPE	PARENT BRECCIA	GEOLOGIC SETTING: INNER IMPACT FORMATIONS	GEOLOGIC SETTING: OUTER IMPACT FORMATIONS	FRACTION OF DISPLACED ROCKS VOL. %; b)	FRACTION OF TOTAL TARGET VOLUME SHOCKED TO >0.1 GPa, VOL. %; c)
(1) FRAGMENTAL BRECCIA		BRECCIA LENS IN CRATER, DIKES IN BASEMENT	BULK OF EJECTA BLANKET	85 - 90	~ 15
(2) SUEVITIC BRECCIA		BRECCIA LENS IN CRATER, DIKES IN BASEMENT	TOP OF EJECTA BLANKET	5 - 10	1.5
(3) IMPACT MELT BRECCIA		CENTRAL BRECCIA LENS, DIKES IN BASEMENT	TOP OF EJECTA NEAR RIM	0.5 - 5	0.1 - 1
(4) IMPACT GLASS	(2)	INCLUSIONS IN TOP SECTION OF BRECCIA LENS	TOP OF EJECTA BLANKET AND DISTANT EJECTA (TEKTITES?)		
(5) CATACLASTIC ROCK	(1), (2), (3)	CLASTS IN BRECCIA LENS, BASEMENT OF CRATER	MEGABLOCKS IN EJECTA BLANKET	a)	~ 83
(6) SHOCKED ROCK	(1), (2), (3), (4)	CENTRAL UPLIFT	CLASTS IN EJECTA BLANKET	a)	

a) ALLOCHTHONOUS CLASTS INCLUDED IN BRECCIA TYPES (1) - (4)
b) DATA IN PART FROM (8) and (31)
c) BASED ON CALCULATIONS OF (15) FOR 1 KM-DIABASE PROJECTILE IMPACTING GRANITE (25 KM/s)

TABLE 3: IMPACT FORMATIONS AT CRATERS IN NON-COHESIVE TARGETS (e.g. SAND)

TYPE OF FORMATION	SHOCK PRESSURE RANGE GPa	FRACTION OF TOTAL DISPLACED MASS[1] %: CRATER CAVITY	EJECTA	TOTAL	SETTING WITH RESPECT TO CRATER
COMMINUTED GRAINS	< 5.5	> 50	1 - 20	~ 4	MAIN MASS INSIDE CRATER; INCREASING FRACTION WITH RADIAL DISTANCE
SHOCK-LITHIFIED GRAINS (AGGLOMERATES)	5.5 - 25	~ 2.5	0.01- 0.2	~ 0.1	
MELT AGGLUTINATES	> 25			~ 0.04	

[1] DATA FOR SMALL SCALE EXPERIMENTS (29); FOR LARGE CRATERS THE MASS FRACTION OF SHOCK-LITHIFIED AND MELTED MATERIAL MAY BE LARGER BY A FACTOR OF 4 TO 8 (COMPARE (15))

TABLE 4: PARTICLE SIZE CHARACTERISTICS OF CLASTS IN TERRESTRIAL IMPACT FORMATIONS

TYPE OF FORMATION	PARTICLE SIZE RANGE (ORDERS OF MAGNITUDE): INNER IMPACT FORMATION	OUTER IMPACT FORMATION
SINGLE MEGABLOCKS	< 100 m	< 1000 m
FRAGMENTAL BRECCIA	µm - deca-m	µm - deca-m
SUEVITIC BRECCIA	µm - dm	µm - dm
IMPACT MELT BRECCIA		
BASAL SECTION	µm - m	-
MIDDLE SECTION	µm - cm	-
UPPER SECTION	µm - dm	-
IMPACT GLASS	µm - cm	µm - cm

TABLE 5: COMPOSITIONAL VARIATION OF IMPACT MELTS IN TERRESTRIAL CRATERS WITH CRYSTALLINE TARGET ROCKS; DATA FROM (8), (24), (7), (23) AND (5)

CRATER	AVERAGE SiO_2-CONTENT OF MELT wt.%	STANDARD DEVIATION 1σ IN MELT SiO_2	STANDARD DEVIATION 1σ IN MELT Al_2O_3	STANDARD DEVIATION 1σ IN TARGET SiO_2	STANDARD DEVIATION 1σ IN TARGET Al_2O_3
MANICOUAGAN	57.75 (50)	1.21	0.64	9.18	5.67
W.CLEARWATER	59.35 (14)	1.88	0.58	6.95	1.19
MISTASTIN	56.15 (75)	2.01	1.94	7.83 (3)	6.91
LAPPAJÄRVI	66.99 (7)	0.98	1.67	8.95 (5)	1.34
RIES					
SUEVITE MELT	63.99 (46)	1.31	0.34	9.45(23)	1.81
POPIGAI					
MELT SHEET	63.13 (22)	1.22	0.53		
SUEVITE MELT	63.11 (14)	4.03	1.12		

NUMBER OF ANALYZED SAMPLES IN PARENTHESES

The proportions of various breccias may be based on the total volume of rocks shocked to pressure greater than about 0.1 GPa, the inferred estimate for the outer limit of brecciation. In this case, autochthonous cataclastic rocks and shocked rocks of the crater basement represent a considerable volume fraction (Table 2). The ratio of allochthonous, polymict breccias to monomict brecciated and shocked lithologies of the crater basement is about 1 : 5 in this case. This may be of importance for the interpretation of planetary impact formations resulting from multiple cratering.

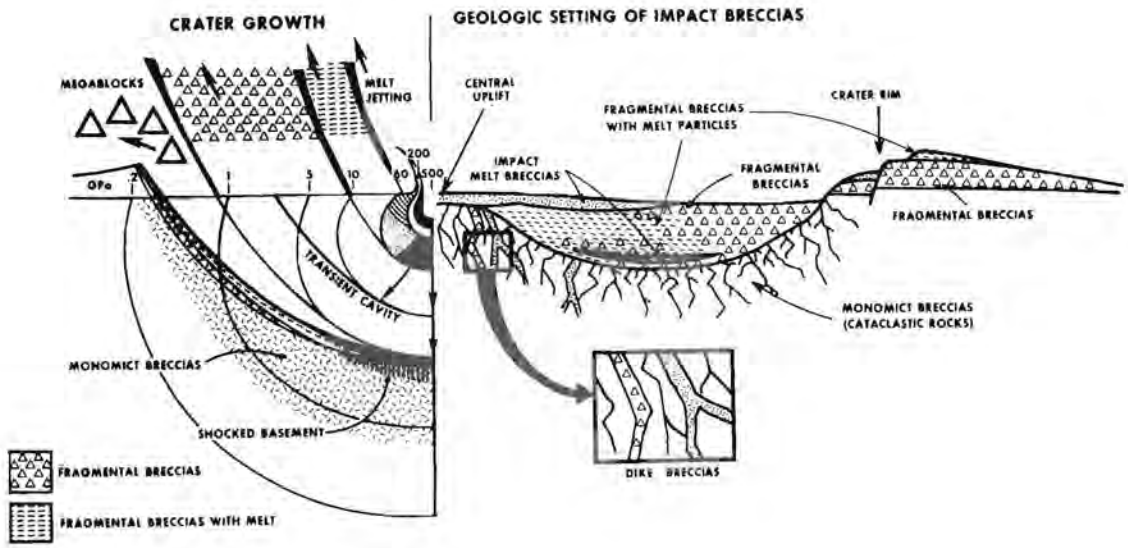

Fig. 1: Formation (left) and geologic setting (right) of impact breccias in a medium-sized complex crater with central uplift (modified after Stöffler, 1981). Left: Shock zones and crater growth (shaded lines above surface indicating ejecta plumes at subsequent times): compressed projectile and melt lining transient crater floor are given in black. Right: schematic cross section after crater modification. The basal melt sheet refers to the special case of Boltysh crater (Yurk et al., 1975). For data sources of this model see Stöffler, 1981.

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Magnetic and thermal history of the brecciated chondrite Abee

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The meteorite Abee is a type 4 enstatite chondrite with many om-size clasts. The paleomagnetic conglomerate test was applied to these clasts, to study the thermal and magnetic history of the meteorite. The directions of magnetization in mutually oriented clasts are significantly different, suggesting that the meteorite was not reheated to temperatures much above 100 C during or after accretion. The matrix seems to be homogeneously magnetized. The matrix magnetization was acquired either during the accretionary process at low temperature or during a brief shock reheating process.

The above thermal history inferred from the magnetic study is consistent with the results of a metallographic study by Herndon and Rudee (1978) and the fact that Abee is highly enriched in volatile elements (Ganapathy and Larimer, 1980).

The strength of the magnetic field was estimated to be 10 Oe using the Thellier method.

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MINERALOGICAL CHARACTERISTICS OF POLYMICT BRECCIAS ON THE HOWARDITE PARENT BODY AND THE MOON. Hiroshi Takeda, Mineralogical Institute, Faculty of Science, University of Tokyo, Hongo, Tokyo 113, Japan.

Comparative studies of pyroxenes in polymict breccias of the howardite parent body and of the lunar highland, have been providing us with a better understanding of the nature and evolution of planetary regoliths. Investigations on pyroxenes in early crustal cumulates found in achondrites and lunar highland rocks have been published (Takeda et al., 1979). We proposed that the polymict eucrites contain essentially the entire range of pyroxene components within the primitive eucritic crust. We suggested that the closest lunar analogue of the polymict eucrites and howardites is a light-matrix breccia 60016,97, which contains pyroxenes known from the major types of plutonic-textured lunar highland rocks. Comparison of basaltic clasts in lunar and eucritic polymict breccias revealed that the lunar KREEP breccias might have been produced by impacts of meteorites into a closely related set of lava units together with pre-existing crust (Takeda et al., 1980). Mesosiderite regolith has been studied by Delaney et al. (1980). In spite of the above extensive studies of local interest, a few comprehensive comparative studies on two primitive planets have been undertaken to elucidate a general model of breccia formation. Comparison was made of pyroxene mineralogy of many polymict eucrites and howardites, which have been recovered from Antarctica (Takeda and Yanai, 1981; Wooden et al., 1981), with that of the lunar analogues in order to gain better understanding of the differences in crust formation and impact process.

The variety of Antarctic polymict eucrites and howardites, were interpreted in terms of a simple model involving impacts of various-sized meteorites into a layered crust of the howardite parent body. Regional differences in breccia-unit distribution on the parent body are also suggested.

Polymict eucrite is defined as a polymict breccia of a eucritic composition with lithic and mineral fragments of various types of eucrites, e.g., cumulate, ordinary, and surface eucrites (Takeda, 1979) and without significant amounts of diogenitic components (less than 10% primary orthopyroxenes from diogenites). A eucrite parent body is commonly used terminology for their parent body, but the howardite parent body proposed by the author (Takeda, 1979) may be a better terminology.

All polymict breccias found to date except ordinary howardites are tabulated in Table 1. In this table, several meteorites in the Yamato-79 collections were added, but those of the 1979 U. S. collection are not included because of a lack of information. They are grouped into five subgroups and are arranged in order of depths of excavation by hypothetical impacts as: (1) Shallow (PE in Table). Yamato-74159 is one of the first polymict eucrites described from Antarctica (Miyamoto et al., 1978; Takeda et al., 1978). A similar meteorite was also found in the Allan Hills region, Antarctica (Miyamoto et al., 1979). The recognition of this type meteoritic breccias is based on our finding of chemically zoned pyroxenes with a Mg-rich core, in Pasamonte. This surface-type eucrite was called unequilibrated eucrite (Reid et al., 1979), but the degree of zoning depends on the crystallization condition. There are two major chemical trends of pyroxene. The Pasamonte trend shows Ca-enrichment parallel to the Fs-Hd join at about the same Fe/(Fe+Mg) ratios as those of ordinary eucrites and the Y-75011 clast trends show little Ca-enrichment in the middle of the pyroxene quadrilateral and Fe-enrichment after this gap. The exsolution textures of pyroxenes in the ordinary eucrites or equilibrated eucrites of Reid et al. (1979) in polymict eucrites are more diverse than those of non-polymict eucrites. Y-790266 contains a large clast of fine-grained ordinary eucrite with a uniform pyroxene composition. The abundances of two types of eucrite differ from one polymict eucrite to another. Y-74450 is rich in surface eucrites with a variolitic texture. This group of polymict eucrites was interpreted to be produced by impacts down to the bottom of the ordinary eucrite layer (Fig. 1). However, there may be lateral variations.

(2) Intermediate (PEC). In addition to the pyroxenes mentioned in the shallow group, polymict eucrites of this group contain fragments of pyroxenes in cumulate eucrite such as Moama. Some pyroxenes of ordinary-eucrite type show exsolution lamellae coarser than those in ordinary eucrites but no inverted pigeonite of Moore County type has been detected. Round clasts of the surface type eucrite are still abundant. The impact for this group may have excavated materials down to the cumulate eucrite layer.

(3) Slightly deep (PED). This group is intermediate between polymict eucrite and howardite. Because the amount of diogenitic orthopyroxene is small, it should be called polymict eucrite with minor diogenite. We thought at one time that Macibini reported by Reid (1974) is the first example of polymict eucrite. However, a recent examination by Mason et al.(1979) mentioned the presence of orthopyroxene as Mg-rich as Fs_{19}. Macibini may belong to this group. The meteorite impact may excavate materials of a very upper portion of the diogenitic mantle.

(4) Deep (HO). All known howardites (Labotka and Papike, 1980; Prinz et al., 1981) belong to this group. We identified a new howardite in the Yamato-79 collection (Takeda and Yanai, 1981). Greenish or yellowish pyroxene fragments are common and have been identified as orthopyroxene by the single crystal X-ray method. This type of polymict breccia is so abundant that it should be an abundant lithology on the parent body.

(5) Deepest (HOD). Polymict breccias of this group are rich in the diogenite components, but still contain ordinary eucrite clasts and pyroxene fragments similar to Yamato-75032. It can be called 'polymict diogenite'. The most Mg-rich orthopyroxene is very poor in Ca contents and approaches to that in Steinbach. To excavate materials of the deepest portion of the diogenitic mantle, the impact must be very large scale. It may correspond to the large multi-ring basin on the howardite parent body, such as Mare Imbrium on the Moon. Kapoeta (Wilkening et al., 1971) and Frankfort belong to this type.

It is to be noted that no Mg-rich olivine, residues of partial melting, nor rocks of source regions have ever been recovered in polymict breccias (Delaney et al., 1980). The evidence is in favor of the above layered crust model.

In summary, the variety of polymict eucrite and howardite can be explained in terms of impacts of meteorites into a primitive layered crust with pyroxene from rapidly cooled to very slowly cooled varieties (Takeda, 1979). The four different schematic models of impact are shown in Fig. 1. Of course, there may be a local difference in the thickness and components of each layer. Two types of the zoning trends of pyroxene found in clasts from Y-75011 and ALHA77302, respectively, may represent two different lava units. Absence of the Moore County-type inverted pigeonite in Y-75015, and of the Binda-type in ALHA78006, suggest that there are only one cumulate eucrite in certain area.

Four different type of breccia might have been distributed on the surface of the parent body. Presence of large clasts of surface eucrite in polymict eucrites implies that original lava unit may be left intact on the surface. Wide area of the surface before destruction might have been covered by the diogenite-rich howardites because a large basin forming impact is

Table 1. Polymict eucrites and howardites arranged in order of excavation by hypothetical impacts.

Excavation	Meteorites	Weight	Ref.
PE	Y-74450	235.6	a,b
	Pasamonte	-	a
	Y-74159	98.2	a,b
	Y-75295	8.8	i
	Y-75296	8.6	i
	Y-75307	7.9	i
	ALHA 76005	1435.	c
	ALHA 77302	235.5	i
	ALHA 78040	211.7	h,j
	ALHA 78132	656.0	h,j
	ALHA 78165	20.9	h,j
	Bialystok	-	k
	Nobleborough	-	k
	Y-790122	109.5	l
	Y-790260	433.9	l
	Y-790266	208.0	l
PEC	ALHA 78158	15.1	h,i,j
	Y-75011	121.5	e
	Y-75015	166.6	e
PED	ALHA 78006	8.0	h,i
	Macibini	-	d
HO	Y-790727	120.4	l
HOD	Frankfort	-	f,g
	Y-7308	480	b,g

a: Takeda et al., 1978, b: Miyamoto et al., 1978, c: Miyamoto et al., 1979, d: Reid, 1974, e: Takeda et al., 1979a, f: Labotka and Papike, 1980, g: Takeda et al., 1976, h: Takeda et al., 1979b, i: Takeda and Yanai, 1981, j: Sato et al., 1981, k: Mason et al., 1979, l: This study.

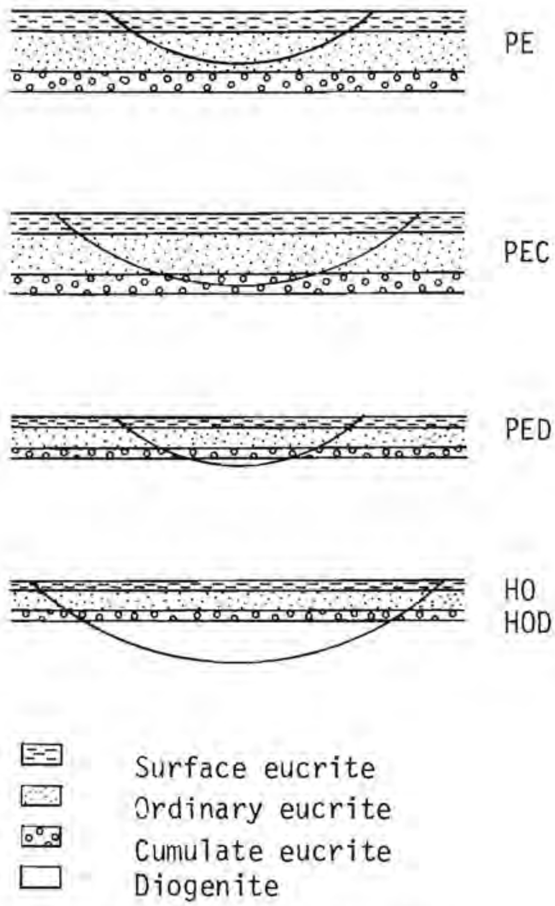

Fig. 1. Schematic models of four impact types into the layered crust of the howardite parent body, which produce various polymict eucrites (PE, PEC, PED) and howardite (HO,HOD).

required to excavate the deep seated rock type such as diogenites. This expectation has been supported by observational rotational studies of 4Vesta by Gaffey (1981), who discovered both orthopyroxene-rich spot and augite-rich spot on the surface.

In contrast to the simple model of the howardite breccia, the lunar analog show complexity in their textures, composition and pyroxene mineralogy. Some highland breccias (e.g. 60016) contain pyroxenes that are not necessarily geneticaly related; that is, they are not a product of a one-step differentiation sequence or a single crystallization trend. Some KREEP-rich breccias contain local rock types. Degree of thermal metamorphism in the hot ejecta blanket is high for some lunar breccias.

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COMMENT: Problems Regarding Meteorite and Lunar Chronology

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There is a significant problem regarding the chronology of both meteorites and lunar samples in the ages determined from the various chronologic systems. The 4.55 Gy U-Th-Pb ages of chondrites (1) are significantly older than the ~4.50 Gy Rb-Sr ages (2) and 4.48 ± .03 Gy Ar-Ar ages obtained on unshocked ordinary chondrites (3). It is not known whether these differences correspond to errors in the half-lives of the parent isotopes or wether the discrepances are related to differences in the closure temperatures of the various systems or to metamorphic events. Although the Rb-Sr and U-Th-Pb systems of most achondrites have been disturbed by later events, the Sm-Nd system provides a ~4.55 Gy age for nearly all achondrites (4), and Lu-Hf isotopic data of brecciated and cumulated eucrites plot on a single isochron (5). However, the Sm-Nd and Lu-Hf methods are not precise enough to resolve small age defferences among chondrites. A similar situation exists with lunar samples. U-Pb and Rb-Sr apparent ages of the lunar crust are not in agreement (6). The U-Pb data are consistent with a major event at ~4.4 Gy ago whereas Rb-Sr data suggest a ≤4.3 Gy age (6). Furthermore, Rb-Sr (7) and Sm-Nd (8) internal isochron ages for lunar troctolite 76535 were not in agreement. At least some of these discrepancies can be attributed to later thermal events. However, until the age differences in samples with simple histories can be resolved, age information from complex samples such as lunar breccias must be viewed with caution.

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PETROLOGIC COMPARISON OF LUNAR AND METEORITIC BRECCIAS. G. Jeffrey Taylor. Inst. of Meteoritics and Dept. of Geology, Univ. of New Mexico, Albuquerque, NM 87131.

Comparisons among terrestrial, lunar and meteoritic breccias can lead to a better understanding of the processes involved in their formation (e.g., Stoffler et al., 1979; Prinz et al., 1977; Floran 1978; Floran et al., 1978). Such comparisons, however, are not straight-forward and if not well thought out can be more misleading than informative, for these reasons:

1) Lunar samples come from one body whose general geological features are well known. Meteorites come from numerous poorly characterized objects with diverse histories.

2) The moon is much larger (1738 km in radius) than meteorite parent bodies, which are generally thought to be tens to hundreds of kilometers in radius. The smaller size of meteorite parent bodies leads to smaller gravitational fields (hence different cratering phenomena), faster cooling, more severe impact effects (Cintala et al., 1979, Horz and Schaal, 1981), and the possibility that features developed during the accretion of meteorite parent bodies are preserved. Furthermore, it is possible for meteorite parent bodies to be disrupted and then reassembled (Davis and Chapman, 1977; Hartman, 1979), possibly leading to greater excavation depths than even basin-forming impacts can yield on the moon, 30-60 km (Grieve, 1980).

3) Lunar breccias are basaltic to feldspathic in composition. Some meteorite breccias resemble lunar compositions, but most are ultramafic (chondrites) or metal-rich (mesosiderites).

4) Our sampling of the moon is not adequate to fully understand its evolution, but it is much better than our sampling of any of the numerous meteorite parent bodies. We do not know if we have sampled the major lithologies present in, for example, the eucrite parent body, or if some types of meteorites have not been sampled because they are too friable to survive ejection from their parent objects or passage through the earth's atmosphere.

LUNAR BRECCIAS AND THEIR GEOLOGIC CONTEXT: INFERENCES FOR METEORITES

Stöffler et al. (1979) used field relationships of terrestrial impact breccias to place lunar breccias into their geologic context. In this section I apply the approach to meteorite breccias, using the classification recommended by Stöffler et al. (1980). Examples of each breccia type appear in Table 1. For reviews of the petrology of lunar breccias, see Irving (1975), James (1977), Simonds (1975), Simonds et al (1976a, 1977), Warner et al. (1977), and Ryder (this volume). For meteoritic breccias, see Wahl (1952), Wilkening (1977), Wasson and Wetherill (1979), and Keil (this volume).

Cataclastic breccias

These are monomict breccias with textures dominated by intergranular brecciation; some may be recrystallized. Lunar ferroan anorthosites are commonly cataclastic (Dowty et al., 1974). The best meteoritic analogs are the enstatite achondrites (aubrites), which are coarse-grained, crushed pyroxenites (Watters and Prinz, 1979). Most eucrites are also monomict, consisting of crushed fragments of basalt. Cataclastic rocks occur as clasts in the deposits that make up continuous ejecta blankets around craters, as clasts within impact melt rocks, or as clasts within breccias formed when material falls back into a crater cavity (Stöffler et al., 1979). Meteoritic cataclastic rocks may have formed in any of these ways, plus during the breakup and subsequent reassembly of their parent bodies.

Dimict breccias

These are composed of two distinct lithologies, one of which is intrusive into the other, producing vein or dike-like structures. In lunar dimict

Table 1. Breccia types and examples

Breccia Type	Lunar Examples	Meteoritic examples
Cataclastic rocks	67955,72415 78527	Enstatite achondrites (e.g., Norton County) Eucrites
Dimict breccias	15445,61015, 64475	Cumberland Falls enstatite achondrite
Regolith breccias	14055, 60255, 79135	Gas-rich chondrites (e.g., Weston) Howardites (e.g., Kapoeta)
Fragmental breccias With cogenetic melt frags.	14063, 67015, 67915	Shaw chondrite
Without cogenetic melt frags.	76255	Slightly recrystallized mesosiderites (e.g., Mount Padbury) Polymict eucrites (e.g., ALHA78040) Some LL chondrites (e.g., Kelly, Siena)
Melt breccias Clast-poor	14310, 68415, 76215	Lithic fragments in chondritic breccias (e.g., Plainview) Pinnaroo mesosiderite
clast-bearing	14305, 60335, 76295	Lithic fragment in Adams County chondrite
clast-rich	14171, 14306	Simondium and Hainholz mesosiderites Chondrites like Point-of-Rocks
Glassy melt breccias	78526	Clasts in howardites (e.g., Bununu)
Granulitic breccias	79215, 76230	Equilibrated LL chondrites Recrystallized mesosiderites (e.g., Clover Springs, Emery, Bondoc) Landes (IAB iron)

breccias such as "black and white" rocks 15445 or 64475 (James, 1977; Ryder and Bower, 1977; Warner et al., 1973), the intrusive lithology is usually a melt rock that contains clastic debris. Pallasites are possible meteoritic analogs in which molten metal was mixed with dunitic rock (Scott, 1977). The only other potential meteoritic analog is the Cumberland Falls meteorite, which consists of a light-colored, cataclastic, enstatite achondrite and a dark-colored, chondritic portion (Binns, 1979); neither is an impact melt, however. Most dimict breccias are produced when impact melt intrudes solid, weakly-shocked rocks, such as in the floors of large, complex craters (Stöffler et al., 1979).

Regolith breccias

These are polymict breccias formed by shock lithification of unconsolidated, fragmental regolith material. Lunar regolith breccias contain the same constituents as does the unconsolidated lunar regolith: brown, swirly glasses, glass spherules, a diverse collection of comminuted rock and mineral fragments, and high content of rare gases and particle tracks implanted by the solar wind and solar flares. Much more attention has been paid to unconsolidated lunar regolith samples than to samples of lunar regolith breccias. This is unfortunate because we have no samples of unconsolidated meteoritic regoliths. Nevertheless, it appears that regolith breccias reflect the nature of the regolith in which they were made. For example the amount of brownish glass in regolith breccias correlates with the amount of solar gases (Drozd et al., 1976), just as agglutinate abundances in lunar soils correlate with solar gas contents, and chemical variations with grain size in regolith breccia 14301 mimic variations observed in soil samples (Papike et al., 1981). Some differences are obvious, but understandable; for example, though abundant in the lunar regolith, agglutinates per se are rare in lunar regolith breccias, but the brownish glass that characterizes agglutinates is abundant in the breccias. For more details on the lunar regolith see McKay (this volume).

The broad features of the processes operating in the lunar regolith are understood reasonably well (Heiken, 1975). As a fresh deposit of bedrock is exposed to meteoroid bombardment it decreases in grain size, agglutinates begin to from in it and increase in abundance, the ratio of mineral to rock fragments increases, and the content of implanted solar gases increases. At any time, addition of fresh bedrock ejecta (immature regolith) or of more mature soil can change the petrologic characteristics of a given volume of regolith. Similar processes probably operate on meteorite parent bodies. Meteorite regolith breccias contain more than 3000×10^{-8} cc/g (STP) of ^{4}He (Schultz et al., 1971). Excluding carbonaceous chondrites, they are characterized by a light/dark structure; i.e., light clasts in a dark, fine-grained, unequilibrated matrix. Other meteorites may also have formed in the surface layers of meteorite parent bodies, but either did not acquire solar gases or lost them subsequently. Meteoritic regolith breccias occur among chondrites (Binns, 1968; Dodd, 1974; Fodor and Keil, 1976; Fodor et al., 1976a; Keil and Fodor, 1980; Keil et al., 1969; McSween and Lipschutz, 1980; Noonan and Nelen, 1976; Scott and Rajan, 1981; Van Schmus, 1967) and howardites (Bunch, 1975; Duke and Silver, 1967; Dymek et al., 1976; Fredriksson and Keil, 1963; Fuhrman and Papike, 1981; Hewins and Klein, 1978; Klein and Hewins, 1979; Lobotka and Papike, 1980; Noonan, 1974).

The petrologic differences between lunar and meteoritic regolith breccias are striking. The most obvious is the abundance of agglutinitic glass: the lunar regolith consists of up to 60% agglutinates (Heiken, 1975) and lunar regolith breccias contain up to 50% agglutinitic glass (Drozd et al., 1976). In contrast, agglutinates are exceedingly rare in meteoritic regolith breccias (Kerridge and Kieffer, 1977, and my own observations). Although not many grain-size analyses of meteoritic regolith breccias have been done, it seems clear that the meteoritic regoliths are coarser grained than their lunar counterparts. This conclusion is based on my observations of hand specimens and thin sections and on grain size analyses done by Bhattacharya et al. (1975), which indicated that meteorite breccias contain a smaller percentage of particles in the 10-70 µm size range than do lunar breccias. These data suggest that meteoritic regoliths are less mature than lunar ones. Possible reasons for this are discussed by Housen et al. (1979), Hörz and Schaal (1981), and Langevin and Maurette (1981); see also reviews in this volume by Housen and by Langevin.

Chemical analyses of grain-size separates of the lunar regolith show that compared with bulk soils, the finest size fractions (<10µm) are enriched in incompatible elements (KREEP) and feldspathic components (Korotev, 1976; Laul et al., 1978, 1979, 1981; Papike et al, 1981). This difference in composition may be caused by mixing of soils with different compositions (Korotev, 1981), by differential comminution (Papike et al., 1981), or by both. Such processes may also operate in meteoritic regoliths, which may explain some of the differences in composition observed for the light (equilibrated clasts) and dark (fine-gained, unequilibrated hosts) portions of chondritic regolith breccias (e.g., Bart and Lipschutz, 1979; Wilkening, 1976). For example, differential comminution of type 3 chondritic rock would result in the finer fractions of the chondritic regolith being enriched in materials derived from the fine-grained matrices of chondrites (Huss et al., 1981), graphite--magnetite aggregates (Scott et al., 1981), or the groundmasses of chondrules.

Meteoritic regolith breccias also contain clasts of "exotic" materials; i.e., rocks drastically different from the local bedrock. The lunar regolith contains exotic clasts, such as nonmare fragments in the regolith developed on mare basalt flows. However, meteoritic regolith breccias contain clasts that probably arrived as projectiles from other parent bodies (Wilkening, 1977). Most of these clasts are carbonaceous chondrites (Bunch, 1975; Fodor and Keil, 1976a; Fodor et al., 1976, 1977; Fredriksson et al., 1969; Fruland et al., 1978; Grossman et al., 1980; Keil and Fodor, 1980; Keil et al., 1969; Kurat, 1975; Leitch and Grossman, 1977; Mason and Nelen, 1968; Noonan and Nelen, 1976; Van Schmus, 1967; Wilkening, 1973, 1976; Wilkening and Clayton, 1974), but a few are of other meteorites such as an H chondrite clast in the St. Mesmin LL Chondrite (Dodd, 1974), an unusual clast in the Bovedy L chondrite (Rubin et al., 1981a) or an LL chondrite clast in the Dimmitt H chondrite breccia (Rubin et al, 1981b). Such foreign material is rare as clasts in the lunar regolith, though its chemical signature is distinct (e.g., Ganapathy et al., 1970). The rarity of recognizable meteorite clasts in the lunar regolith suggests that impact velocities are much greater on the moon than on meteorite parent bodies. This is consistent with other properties of meteoritic regolith breccias, such as the rarity of agglutinates.

Fragmental breccias

Fragmental breccias are composed of clastic material representing a variety of lithologies. They are similar to regolith breccias in that they are clastic (i.e., their matrices are not impact melts), but they differ in not containing the usual set of regolithic components. Stöffler et al. (1979, 1980) distinguish two varieties of fragmental breccias. One type is analogous to terrestrial suevitic breccias and contains cogenetic fragments of melt that have the same compositions as the unmelted clasts. Lunar rocks 14063 (James, 1977) and 67016 (Norman, 1981) are examples. Mesosiderites like Patwar and Crab Orchard (Floran, 1978) may be meteoritic analogs; the Shaw chondrite (Taylor et al., 1979) may also be a meteoritic analog, although it is not polymict. The other type of fragmental breccia is free of cogenetic melt particles. Lunar breccia 76255 (Simonds et al., 1974), gas-poor chondrites like Mezo-Madaras (Van Schmus, 1967) and Bhola, polymict eucrites, LL chondrites like Kelly (Bunch and Stöffler, 1974) and Siena (Kurat et al., 1969), slightly recrystallized mesosiderites (Floran, 1978) and perhaps the North Haig ureilite (Berkley et al., 1980) are melt-free fragmental breccias.

Stöffler et al. (1979) suggest that both types of fragmental breccia could have formed as breccia layers surrounding craters larger than a few hundred meters or as breccia layers within the crater below or intermingled with impact melt sheets. For meteorites, we must add the possibility that fragmental breccias could form during accretion or when a parent body is disrupted but then reassembles.

Impact melt breccias

Impact melts are characterized by igneous-textured matrices. The distinctions between melts produced by endogenous igneous processes and by impact are discussed by Dence (1971), Irving (1975), Simonds et al. (1974) and Floran et al. (1976, 1978b). The chief petrographic criterion is the presence of clastic debris (rock and mineral fragments); in lunar breccias, many clasts are themselves breccias.The texture of the igneous matrix depends on composition and on the abundance of clastic materials incorporated into the melt (Floran et al., 1978b, Simonds, 1975, 1976a,b). The melt composition in a given impact event is uniform throughout the melt sheet and represents the bulk composition of the target rocks (Dence, 1971; Floran et al., 1978b, 1976; Grieve, 1975; Grieve and Floran, 1978; Grieve et al., 1974).

Stöffler et al. (1980) suggest subdividing melt breccias into clast-poor (<10 vol% clasts), clast-bearing (10-25 vol%) and clast-rich (>25 vol%) varieties. Lunar clast-poor melt breccias include 14310 and 68415 (James, 1973; Gancarz et al., 1972; Vaniman and Papike, 1980), which are nearly clast-free, and 76215 (Simonds et al., 1975). Meteoritic equivalents include the Pinnaroo mesosiderite (Floran et al., 1978a) and certain lithic fragments in LL chondrites (Fodor and Keil, 1975) and in other chondritic breccias such as Plainview (Fodor and Keil, 1976a,b; Keil et al., 1980), St Mesmin (Dodd, 1974), Eva (Fodor and Keil, 1976), Oro Grande (Fodor et al., 1972), Abbott (Fodor et al., 1976), Tysnes Island (Wilkening, 1978; Keil and Fodor, 1980), and Supuhee (Leitch and Grossman, 1977). However, there are no known whole chondrites that are clast-poor melt breccias. Clast-bearing breccias are probably the most common type of lunar melt rock; examples include 60335 (Vaniman and Papike, 1980), 14305 (Simonds et al, 1977) and 76295 (Simonds et al., 1975). There are few meteorite equivalents; the best example is a lithic fragment in the Adams County breccia (Fodor et al., 1980). Clast-rich melt breccias are common on the moon; examples are 14171 and 14306 (Simonds et al., 1977). Meteoritic analogs include the mesosiderites Simondium and Hainholz (Floran et al., 1978a), the chondrite Point of Rocks (unpublished work), and perhaps Shaw (Taylor et al., 1979).

Stöffler et al (1979) and Dence (1971) note that impact melts form in craters >1 km in diameter and are usually found on the crater floors below the fragmental breccia pile. They are also found as pods of melt in and beyond crater rims and as dikes intruding the floor and walls of craters. Meteorite breccias probably formed in similar environments.

Impact melt breccias are the most common type of rock in the lunar highlands, accounting for at least 30% of the returned samples (Simonds, et al., 1976a). (My survey of published data suggests that the percentage is closer to 50%, if one excludes regolith breccias from the tally.) They are rare, however, among meteorites. This difference may be caused by a much milder impact history for meteorite parent bodies. A less violent history is consistent with the lack of breccia-in-breccia textures among meteorites, although such structures are the rule among lunar breccias. On the other hand, the smaller number of meteoritic melt breccias may be due to a parent body's inability to withstand a large impact:Lange and Ahrens (1979) have shown that most lunar impact melt breccias were formed in craters >30 km across. Such large craters might disrupt meteorite parent bodies rather than forming extensive volumes of impact melt. Exceptions to the rule are the mesosiderites, a significant percentage of which are melt rocks (Floran, 1978). This hints that they formed on a larger body than did chondrites.

Glassy melt breccias and impact glasses

These are similar in many respects to impact melt rocks, except that their matrices are composed of glass (sometimes devitrified) rather than crystalline material. Most contain clastic debris. Some particles are pure glass; these are usually small (<3 cm). They form when impact melt is dispersed into small particles when ejected from a crater and then quench. Such melts occur as discrete objects formed by small-scale impacts into the regolith (craters in the 10-50 m size range) or as melt inclusions in suevitic breccias, in which case they are associated with craters >1 km in diameter (Stöffler et al., 1979). An example of a lunar glassy melt breccia is 78526 (R. D. Warner et al., 1978). Numerous other examples populate samples of the lunar regolith and regolith breccias. Among meteorites, such glassy objects occur only as clasts in howardites (Hewins and Klein, 1978; Klein and Hewins, 1979; Noonan, 1974).

Granulitic breccias

These are metamorphosed, polymict, fragmental breccias. Their matrices have metamorphic textures, granulitic (anhedral, equant crystals whose boundaries form smooth curves and tend to meet at 120° triple junctions) to poikiloblastic. Mineral compositions can be uniform throughout a specimen (in which case the polymict nature is evident only by variations in modal mineral abundances among clasts) or heterogeneous. Lunar granulitic breccias such as 76230 and 79215 are quite distinctive and most contain between 70 and 80%

plagioclase (Bickel and Warner, 1978; Warner et al., 1977). Meteoritic granulitic breccias are quite numerous: most equilibrated LL chondrites (Mason and Wiik, 1964; Fodor and Keil, 1978), recrystallized mesosiderites such as Clover Springs, Emery and Bondoc (Floran, 1978), and perhaps the IAB iron meteorite Landes (Bunch et al., 1972).

A central question concerning granulitic breccias is the heat source for the metamorphism (Grieve, 1980). Lunar granulitic breccias were held at $\sim 1000^{\circ}C$ for long periods of time (Warner et al., 1977). Similarly, meteoritic granulitic breccias (and equilibrated chondrites in general) were raised to $750-900^{\circ}C$ (Bunch and Olsen, 1974) and cooled slowly (Wood, 1967; Scott and Rajan, 1981). Stöffler et al. (1979) suggested that the metamorphism of lunar granulitic breccias could have taken place when breccia clasts were incorporated into impact melts formed inside large craters. Warner et al. (1977) suggested that the moon experienced an extended period of granulite metamorphism of its outer crust, aided by high heat flow and by intense meteoroid bombardment prior to 4.0 Gyr.

Meteorite granulitic breccias probably formed near the surfaces of their parent bodies (in order to produce polymict, fragmental breccias), but then must have been buried tens of kilometers to cool as slowly as they did. Mesosiderites pose similar problems of slow cooling after compaction (Powell, 1969). A possibility is that some meteorite parent bodies were disrupted while still hot, but then reassembled, causing some surficial fragmental breccias to be buried deeply within the body.

CLUES TO THE ORIGIN OF CHONDRULES

The discovery of glass spheres and quench-crystallized impact melts in lunar soils and regolith breccias was used by some investigators as evidence that most chondrules in chondrites formed by small impacts into the regoliths on chondrite parent bodies (King et al., 1972; Nelen et al., 1972), or at least that some chondrules may have formed by this mechanism (Kurat et al., 1972, 1974; Prinz et al., 1977). However, the notion that a substantial percentage of chondrules formed by impacts onto chondrite parent bodies is demonstrably false. First, chondrules are far less abundant in the lunar regolith, a few % (Heiken, 1975), than they are in chondrites, $\sim$50%. Second, as Kerridge and Kieffer (1977) point out, glass spherules and other chondrule-like objects in the lunar regolith are always accompanied by greater amounts of agglutinates, yet chondrites, even chondrite regolith breccias, contain few, if any, agglutinates. Third, one of the most efficient regolith processes is comminution. The lunar regolith is made up of fragmental material, including many broken glass spheres, yet type 3 chondrites contain mostly unbroken chondrules. In short, only a small percentage of chondrules in chondrites could have formed by impact into a regolith.

Another possibility is that chondrules formed during large impacts on the chondrite parent body. The only appropriate analogs are lunar and terrestrial melt-bearing, suevitic, fragmental breccias, but again chondrites do not resemble such impact deposits: First, chondrites lack the clastic, unmelted debris present in suevitic breccias. Second, chondrules have a broad range of compositions (e.g., Lux et al., 1981), yet as discussed above, melts from impacts tend to be fairly uniform in composition. Third, even if a pile of chondrules could be produced in a large impact event, it is not clear how the other components (metal and fine-grained, FeO-rich silicate matrix) in chondrites were incorporated into the hypothetical pile of chondrules. However, none of these arguments rules out the possibility that chondrules were produced by impacts between small objects prior to the accretion of chondrite parent bodies (e.g., Kieffer, 1975).

ELEMENT MIGRATION

Volatile elements are enriched (relative to Cl chondrites) in the clastic matrices of chondritic regolith breccias (Bart and Lischutz, 1979; McSween and Lipschutz, 1980). These enrichments and the fractionation patterns displayed by the elements might be more comprehensible if we understood how volatile elements are transported during and as a result of impact. Some work on this topic has been reported for lunar breccias and soils (Garrison and Taylor, 1980; Housley, 1979; Housley and Grant, 1976; McKay et al., 1972), but much more needs to be done.

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